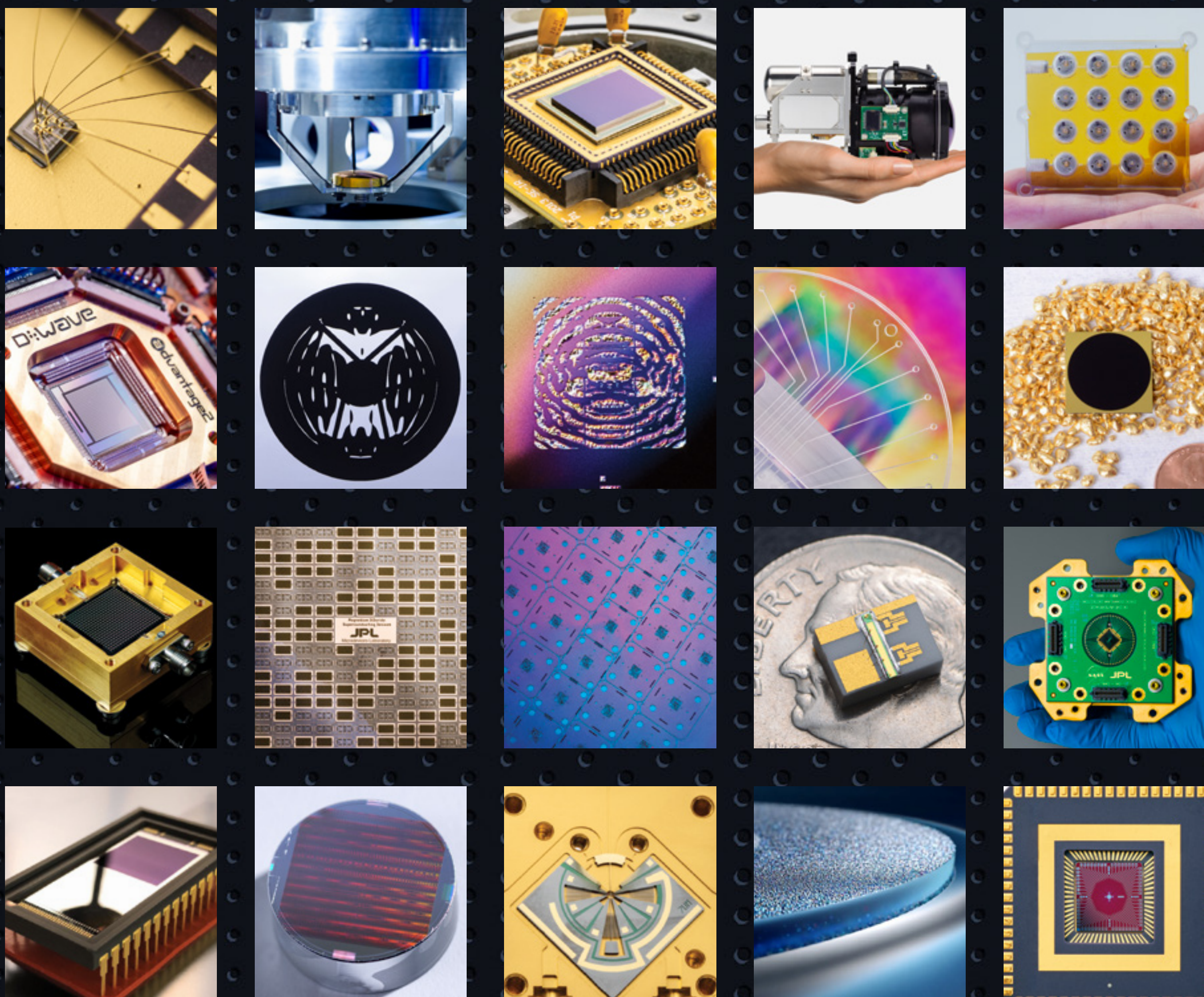
National Aeronautics and
Space Administration

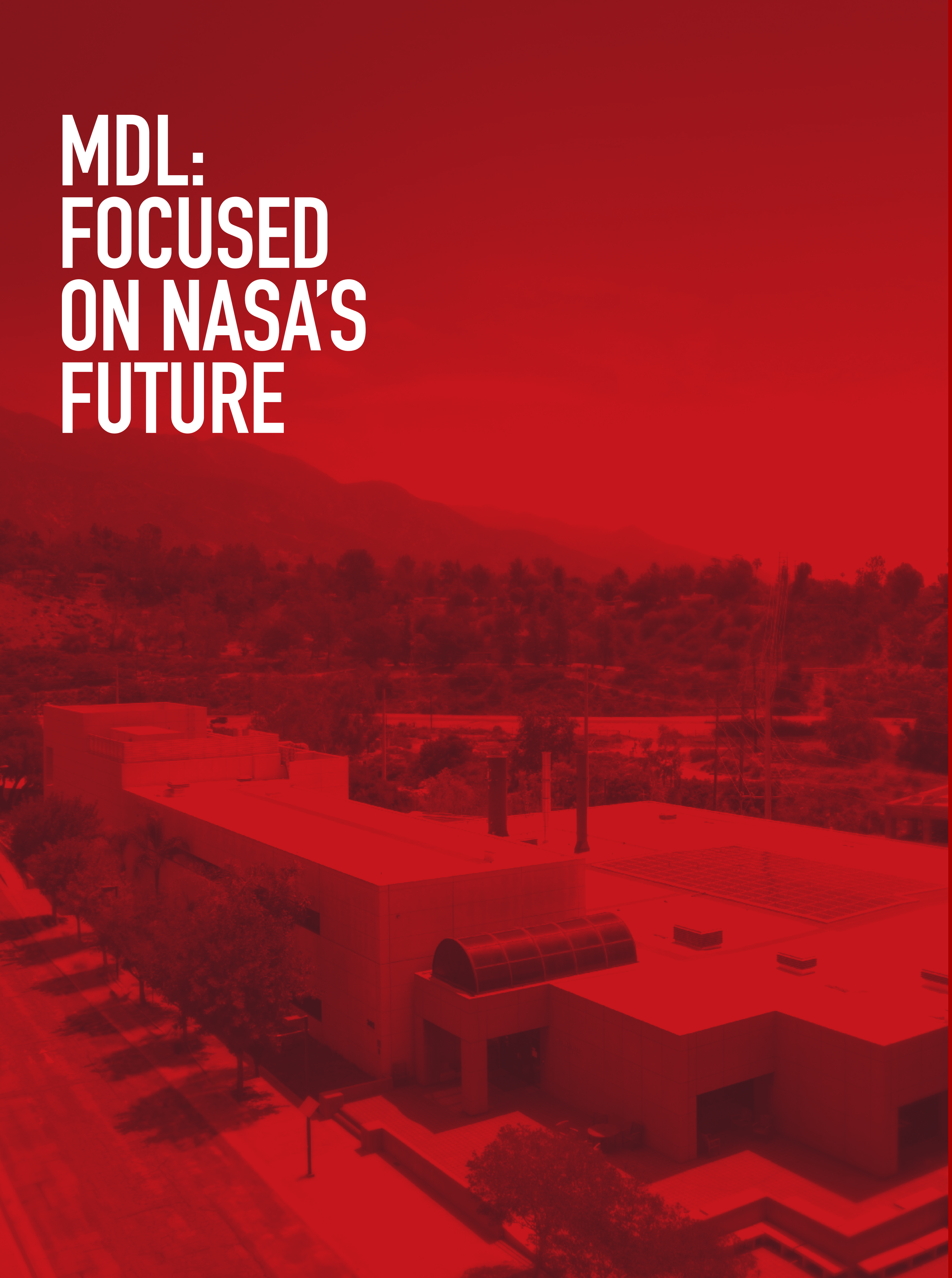


MICRODEVICES LABORATORY
2025 | ANNUAL REPORT

MDL SUPPORTING NASA AND OUR NATION

Jet Propulsion Laboratory
California Institute of Technology

MDL: FOCUSED ON NASA'S FUTURE



MDL TECHNOLOGY INNOVATIONS SUPPORT NEW MISSIONS AND INCREASE SCIENCE RETURNS

For more than 30 years, the Microdevices Laboratory (MDL) has supported NASA missions by developing microtechnologies that meet evolving science and engineering needs.

Aligned with NASA's strategic objectives, MDL contributes to mission proposals, instrument development, and long-term technology planning.

Supported by JPL leadership, the laboratory sustains state-of-the-art facilities and a skilled workforce.

MDL relies on strong collaborations with NASA centers, defense and security agencies, industry, and academia to advance its mission.

DIRECTORS' MESSAGES

Dave Gallagher
Director, Jet Propulsion Laboratory

As we publish the 2025 Microdevices Laboratory (MDL) Annual Report, I am delighted to spotlight MDL for inventing and delivering novel devices that enable unique space-relevant projects, instruments, missions, and capabilities for JPL, NASA, and our nation.

A prime recent example is the High Operating Temperature Barrier Infrared Detector (HOTBIRD), which was inducted into the United States Space Technology Hall of Fame in 2025. This detector has manufacturability and operability characteristics that are critically superior to alternatives and has been rapidly transferred to industry for commercial and defense applications. Consistent with MDL's charter, more advanced HOTBIRD devices continue to be developed at MDL to support NASA and other customers today and in the future.

Looking to even longer wavelengths and greater sensitivities, MDL-invented superconducting Kinetic Inductance Detectors (KIDs) are being advanced for next-generation astrophysics space missions and for unique observational capabilities of critical value to customers here on Earth.

Closer to home, observations made with MDL-enabled instruments during the Eaton and Palisades fires, which severely impacted JPL and our region in 2025, are pointing the way toward future approaches for fire detection, fire fuel assessment, and risk mitigation approaches.

In our core role supporting NASA, MDL is focusing on devices aligned with the Moon to Mars Program, including development of new devices that enable in situ and remote measurements for human exploration throughout our solar system. Innovative devices are being developed to monitor air and water quality and detect fire precursors in space transportation vehicles. Looking to the future, we continue to invest in advanced MDL capabilities, as exemplified by the installation of an ASML high-throughput optical lithography scanner. This scanner will expand and open new domains for the invention, development, and delivery of novel devices.

At this time, I wish to express my gratitude to all those who work in MDL and contribute to its exceptional track record of success for JPL, NASA, and our nation. As you read this annual report and learn about our recent activities, I hope you find connections to your own activities and interests. If you see possibilities for collaboration and partnership, I encourage you to reach out to us. We stand ready to explore all opportunities as we look to the future.

Robert O. Green
Director, Microdevices Laboratory

Today's technologies are tomorrow's missions

First and foremost, I want to recognize the extraordinary work of the MDL team and community for their continued dedication to invent, develop, and deliver novel devices that enable new observations, instruments, missions, and capabilities for NASA and our nation.

2025 has been a challenging year that began with the Eaton wildfire on our doorstep, which has impacted so many of us, our friends, and our colleagues. The MDL operations and safety team kept our facility safe through this event and in the months that followed. This has also been an exciting year, with many exceptional advances in new devices across the broad domains of MDL, which include: submillimeter wave technology, advanced detectors and nanomaterials, superconducting materials and devices, flight imaging systems and packaging, advanced microsensors and microsystems, mass spectrometry, chemical analysis and life detection, and photonics and quantum sensors. Across these domains, we are delivering on our commitments for NASA, developing new opportunities to support other agencies, and, wherever appropriate, transferring new device technologies to industry.

A key milestone this year was the MDL Visiting Committee review. This biannual assessment ensures our activities remain state-of-the-art and aligned with our charter. We are deeply thankful for the committee's rigorous work and the timely arrival of the report. The report is favorable, and we are already moving forward with elements of their actionable recommendations to strengthen MDL for the future.

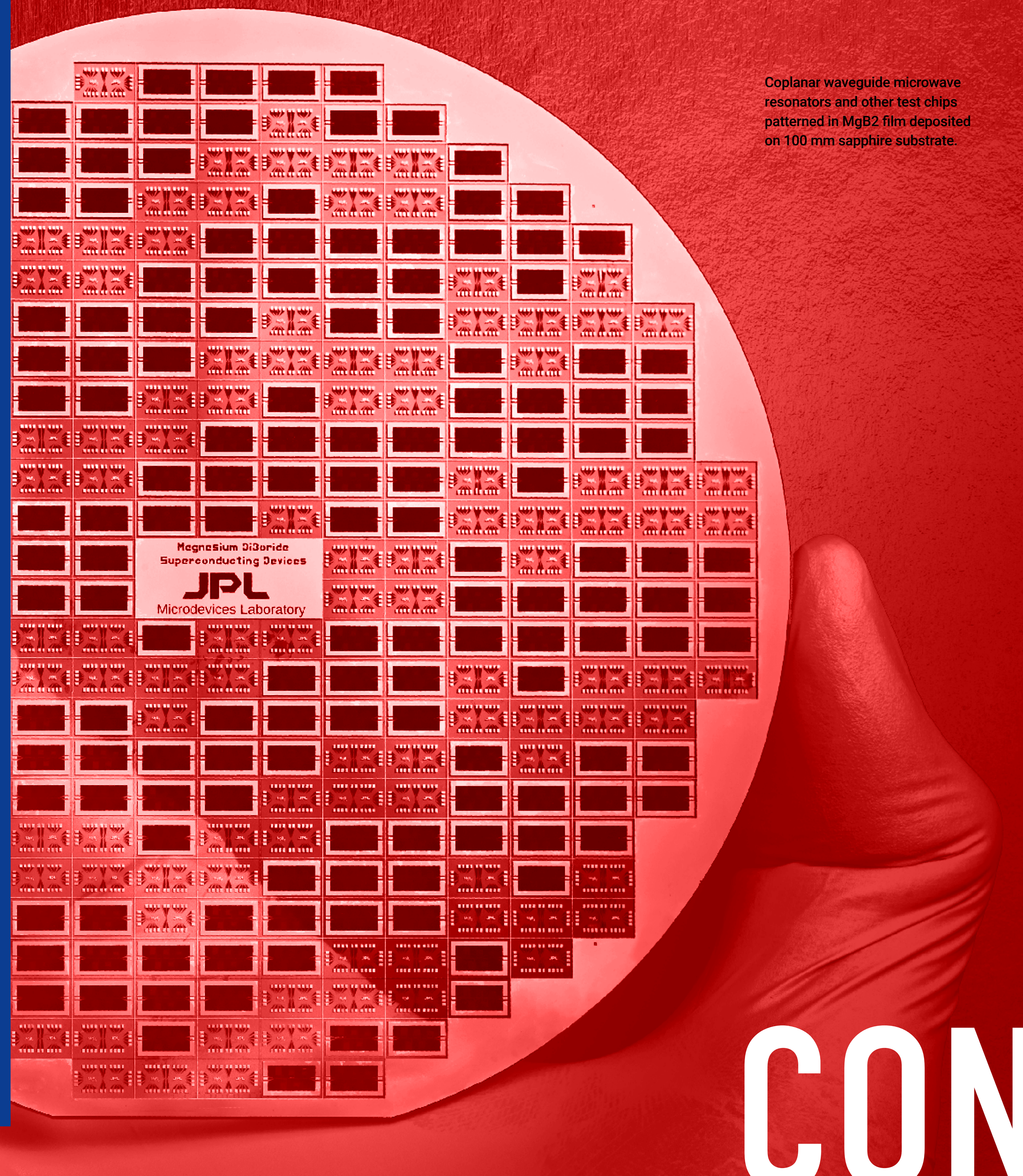
Looking ahead, we are excited to greatly advance our high-throughput optical lithography capability with the installation of an ASML scanner. This high-end infrastructure will enable new pathways for invention of device types across many of our research domains. In the next year and beyond, we will be focused on supporting NASA objectives and initiatives and exploring opportunities for new space-device–relevant activities. I hope you enjoy the contents of this annual report, and I encourage you to reach out if you have questions or see a new opportunity for us to innovate together.

MDL DEVICES AND TECHNOLOGIES CONTINUE TO BE SUCCESSFULLY DELIVERED

Because new technology developments regularly take many years to come to fruition, MDL's rich legacy has been sustained through consistent investment over its history.

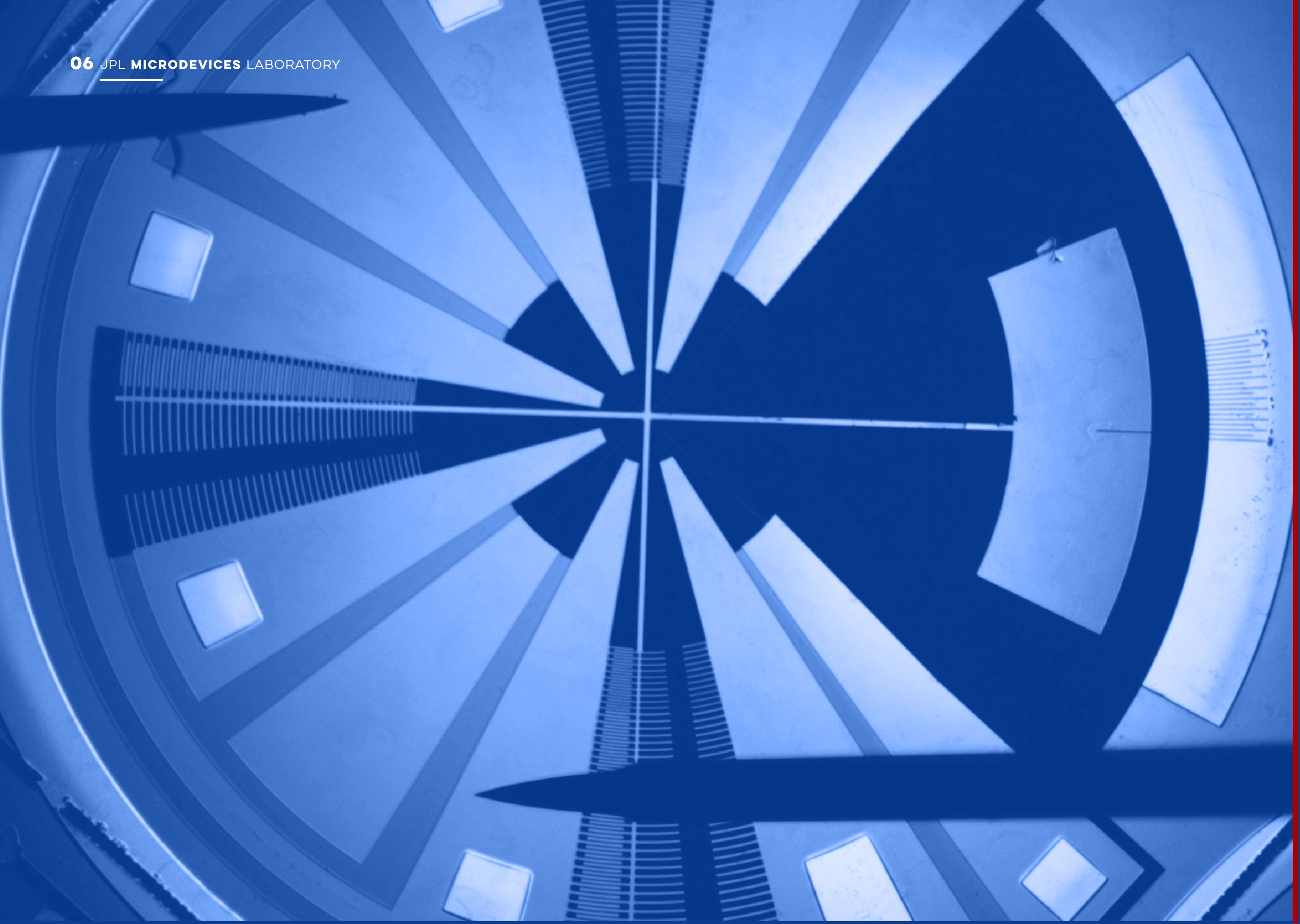
MDL devices and technologies have been successfully delivered for years, with many more in development for deployment in the short- and long-term future.

With its many contributions to JPL and NASA, MDL has been pivotal to these organizations' pasts and core to their futures.



Coplanar waveguide microwave resonators and other test chips patterned in MgB2 film deposited on 100 mm sapphire substrate.

CONTENT



Microscopic view of the device seen from the top while actuated.

MDL's innovations have played important roles on Earth and in space: HOT-BIRD and infrared imaging spectrometry aided firefighting efforts across the US; laser optical systems are being developed to support gravitational analyses for missions to other worlds and defense surveillance on Earth; and new technologies have been designed to test instrument performance under harsh conditions.

These contributions will support mission success well into the future, and their importance has been broadly recognized: in 2024, HOT-BIRD technology was inducted into the Space Technology Hall of Fame, and the Deep Space Optical Communication demonstration and Europa Clipper, which includes the MDL-enabled Mapping Imaging Spectrometer for Europa, were named among Time Magazine's best inventions of the year.

MDL'S CONTINUOUS ACHIEVEMENTS INNOVATIONS

The HyTI 6U SmallSat just seconds after its deployment from the International Space Station (ISS). The large solar panel belongs to the ISS.

MDL experts have spent more than 30 years working on infrared detector and FPA technology. Their transformational work has enabled advances in Earth science, remote sensing medical diagnostics, and defense, among many fields.

Two key innovations developed at MDL have been inducted into the Space Technology Hall of Fame, reflecting the pivotal nature of this technology. Licensing agreements have also enabled the translation of basic research innovations at MDL into commercially viable solutions that benefit industry.

30 YEARS of IR detector research at MDL

Historically, infrared detection has relied predominantly on group II-VI compound semiconductors, most notably mercury cadmium telluride (HgCdTe). Although HgCdTe offers excellent sensitivity across a broad spectral range, the volume market of the infrared focal plane arrays was dominated by indium antimonide (InSb) in the last couple of decades. This was due to InSb's ease of manufacturability and hence lower cost coupled with high pixel operability and manufacturing yield. However, InSb has a fixed cutoff wavelength at 5.5 µm, so that it provides coverage only for the mid-infrared spectral region.

To address these limitations, MDL turned to group III-V compound semiconductors, which offer a more robust and manufacturable alternative. Group III-V materials, such as gallium arsenide (GaAs) and indium phosphide (InP), have strong covalent bonds and mature fabrication technologies, largely developed and refined through decades of investment by the telecommunications industry. They are easier to grow with high crystalline quality and allow for more precise control over doping and layer uniformity.

However, most III-V compounds possess relatively large bandgaps, which limit their ability to detect long-wavelength infrared (LWIR) radiation. Exceptions like Indium Gallium Arsenide (InGaAs) on InSb have been successful in short-wave and mid-wave infrared detection, respectively, but do not provide a complete solution across the wide infrared spectrum.

To overcome this challenge, MDL adopted bandgap engineering approaches using quantum wells and superlattices to tailor the electronic properties of III-V materials, leading to the development of quantum well infrared photodetectors (QWIPs). In a QWIP, electrons are confined within a thin GaAs layer, flanked by barrier layers of $Al_xGa_{1-x}As$.

This structure creates a square quantum well where electrons can only occupy discrete energy levels. When a photon of the right energy strikes the well, it excites an electron from the ground state to an excited state—an intersubband transition—leading to measurable photocurrent.

Molecular beam epitaxy (MBE) enables atomic-scale control over the growth of QWIPs, allowing for the precise tuning of well width and barrier height, and ensuring sharp, high-quality interfaces.

The doping of GaAs with silicon introduces free electrons into the wells, which are necessary for the detector to function. QWIPs are typically stacked in multiple quantum well layers to enhance absorption, especially for wavelengths longer than 5 µm.

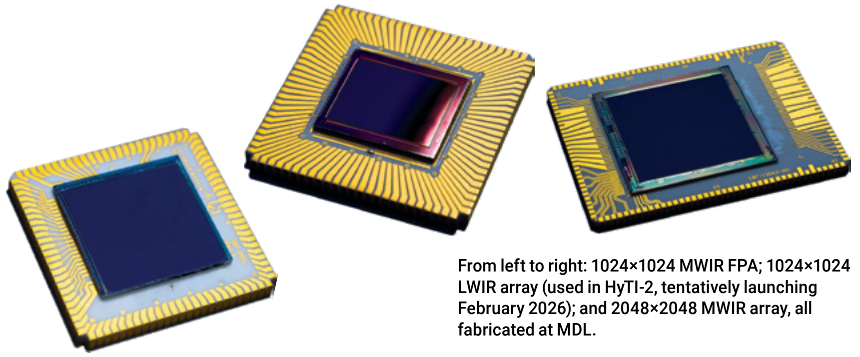
The first QWIP was demonstrated by Barry Levine and colleagues at AT&T Bell Labs. Building on that foundation, MDL significantly advanced QWIP technology by introducing bound-to-quasi-bound transitions, which improved detector efficiency and responsiveness. These innovations led to the first hand-held infrared camera using large-format QWIP focal plane arrays, enabling new commercial and scientific applications.

QWIP technology was licensed by Caltech to QWIP Technologies for defense applications and to Omnicorder Technologies for medical diagnostics. It was also adopted by NASA's Goddard Space Flight Center for use in the thermal infrared imaging instruments on the Landsat 8 and Landsat 9 satellites, which continue to provide vital data for global environmental monitoring.

In 2001, QWIP technology was inducted into the Space Technology Hall of Fame. Established in 1988 by the Space Foundation in collaboration with NASA, the Hall of Fame recognizes individuals, organizations, and companies that have successfully adapted space-based technologies to improve life on Earth. The program also seeks to inspire future innovation in space exploration. Each year, an average of two breakthrough technologies are inducted, selected from nominations submitted by the space community and global space agency technology transfer offices. A panel of experts in space and technology evaluates the nominees, and honorees are formally inducted at the annual Space Symposium. QWIP technology's induction recognizes its transformative impact across the space, defense, environmental, and medical fields.

DEVELOPED AT MDL, QWIPS EXEMPLIFY THE SUCCESSFUL TRANSLATION OF QUANTUM PHYSICS INTO PRACTICAL, HIGH-IMPACT TECHNOLOGY

MDL's next generation of infrared detectors



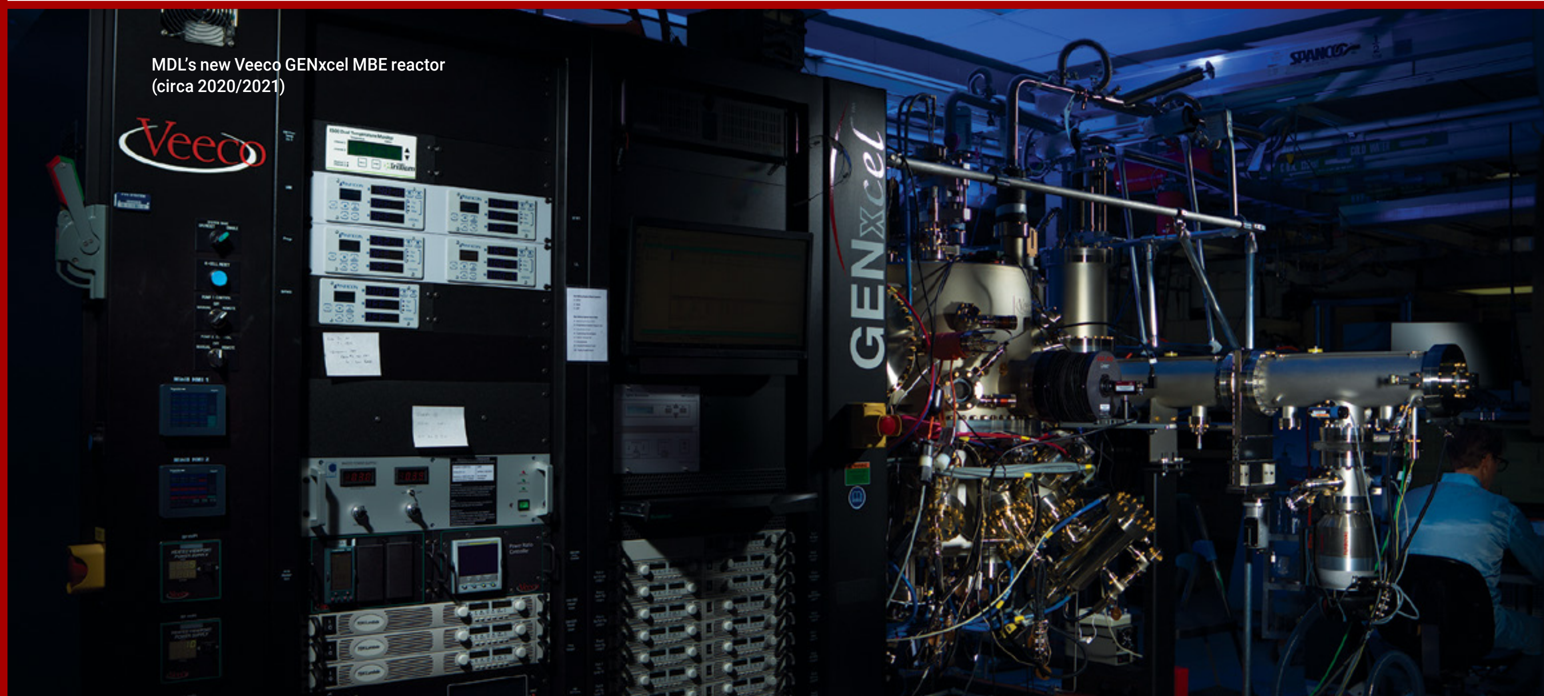
From left to right: 1024×1024 MWIR FPA; 1024×1024 LWIR array (used in HyTI-2, tentatively launching February 2026); and 2048×2048 MWIR array, all fabricated at MDL.

Nearly two decades ago, JPL acquired a Veeco Gen III molecular beam epitaxy (MBE) system for MDL, laying the foundation for one of the most groundbreaking advances in infrared detection technology. Initially, MDL focused on fabricating gallium antimonide (GaSb)/indium arsenide (InAs) strained-layer superlattices (SLS), which were at the forefront of infrared detector development. In 2009, this work culminated in the invention of the complementary barrier infrared detector (CBIRD), a novel architecture that remains one of the highest-performing technologies using GaSb/InAs SLS materials. However, the true leap forward came with the invention of a gallium-free alternative: The indium arsenide antimonide (InAsSb)/InAs SLS-based high operating temperature (HOT) barrier infrared detector, now widely known as HOT-BIRD or HOT-SLS. Developed at MDL and led by Dr. Sarath Gunapala, this innovation marked a transformative shift in infrared detection. Unlike traditional detectors that require cryogenic cooling, HOT-BIRD technology can operate at significantly higher temperatures.

This reduction in cooling demand translates into lower system size, weight, and power consumption—key metrics that unlock the potential for miniaturized, affordable, and high-performance infrared instruments. Infrared detectors play a vital role in sensing mid-wave infrared (MWIR, 3–5 µm) and LWIR, 7–12 µm radiation, which are essential for observing Earth's land and sea surface temperatures, detecting wildfires, and supporting various defense and scientific missions. Historically, these infrared remote sensing instruments are bulky due to large cryocoolers and calibration systems. InSb detectors are robust but limited by lower operating temperatures and fixed wavelength responses. HOT-BIRD technology changed that. It combines the adjustable spectral tunability of HgCdTe with the manufacturing robustness and scalability of InSb-based systems. Moreover, HOT-BIRD detectors do not rely on gallium-based compounds, which simplifies fabrication and enhances long-term reliability.

These gallium-free SLS detectors are manufactured using a process in which layers of atoms are precisely deposited on a substrate, forming engineered crystal structures with tailored bandgaps. The result is a highly customizable infrared sensor with wide-ranging applicability across the space, defense, and commercial domains. The HOT-BIRD effort received significant backing from multiple government programs, including the Department of Defense's Vital Infrared Sensor Technology Acceleration (VISTA) initiative. MDL served as the Government Trusted Entity in the nation's largest infrared detector development campaign, leading innovations and transferring mature technologies to US industry through the VISTA Industry Consortium.

This partnership enabled rapid technology infusion into major defense systems, saving the US government billions of dollars while strengthening domestic industrial capabilities.



MDL's new Veeco GENxcel MBE reactor (circa 2020/2021)

HOT-BIRD joins Space Technology Hall of Fame

HOT-BIRD induction ceremony held at the 40th Space Symposium in Colorado Springs. Left to right: Dr. Lori Glaze (NASA), Dr. Sarath Gunapala (MDL), Dr. Laurie Leshin (former JPL Director), and Dr. Heather Pringle (Space Foundation CEO, former USAF Lab Director).

Beyond defense, HOT-BIRD technology has been a key enabler for cutting-edge Earth observation missions. For example, the Hyperspectral Thermal Imager (HyTI), a 6U SmallSat launched on March 21, 2024, was built around it. Funded under NASA's In-Space Validation of Earth Science Technologies (InVEST) program, HyTI provides high-resolution thermal imaging for hydrological and agricultural applications, helping to monitor water resources and land surface temperature. Its successor, HyTI-2, scheduled for a 2026 launch, will employ a significantly larger FPA for even greater performance.

Outside government missions, gallium-free superlattice detector technology is now being commercialized across multiple sectors. Industry leaders such as L3Harris, Teledyne-FLIR, RTX, and Lockheed Martin have adopted HOT-BIRD technology in products for high-speed thermal imaging, environmental monitoring, security and surveillance, search and rescue, medical diagnostics, and industrial inspection. Its compact form factor and reduced cooling needs make it ideal for portable systems, unmanned aerial vehicles (UAVs), and even CubeSats, opening possibilities never before attainable with traditional infrared technologies.

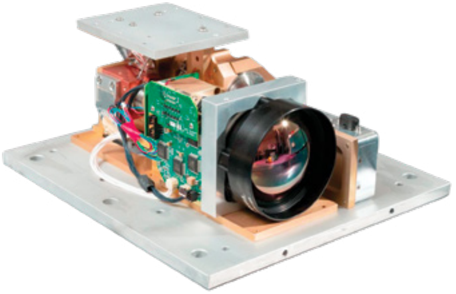
The team at MDL continues to refine and expand this technology through collaborations supported by NASA Research Opportunities in Space and Earth Science (ROSES), the Advanced Component Technology (ACT) program, and the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) initiative.

From ground-based to airborne and space-based platforms, HOT-BIRD detectors are being designed to support diverse scientific missions, including planetary exploration, atmospheric studies, and precision agriculture. The HOT-BIRD team's accomplishments have earned widespread accolades. The MDL group working on infrared detector technology received the prestigious Herschel Award and Levinstein Award from the Military Sensing Symposia Committee for significant contributions to infrared device science.

In 2018, the team was honored with the SPIE George W. Goddard Award for excellence in optical instrumentation. Most notably, in 2025, HOT-BIRD technology was inducted into the US Space Technology Hall of Fame—an accolade that underscores its transformative impact and the benefit this technology has had not just in space but also on Earth. HOT-BIRD is more than a detector: It is a platform for innovation. By combining material science, advanced fabrication techniques, and mission-driven design, it enables the next generation of IR sensing.

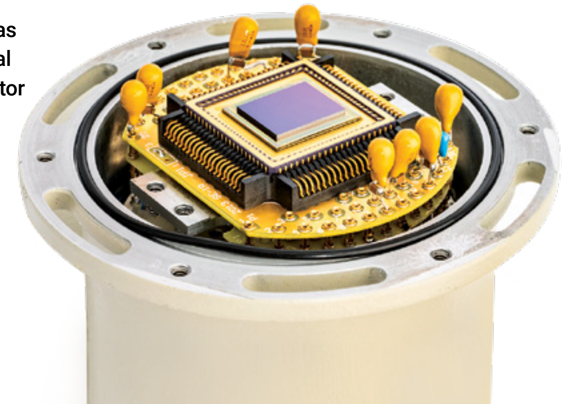
Whether studying space science, responding to natural disasters such as wildland fires, or safeguarding national security, gallium-free HOT-BIRD detector technology has redefined what is possible in infrared remote sensing and will continue to empower discoveries for decades to come.

QWIP technology was inducted into the Space Technology Hall of Fame in 2001.



2U HyTI instrument based on HOT-BIRD FPA.

24-μm pixel pitch, 640 × 512 pixel LWIR HOT-BIRD FPA.

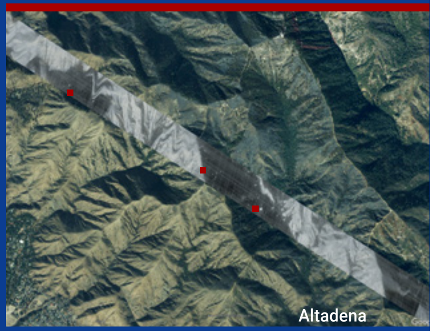


A HOT-BIRD's eye view of wildfires using c-FIRST

Palisades Fire: Burn scars and active hotspots detected using 3.85 μm channel overlaid on Google Earth.

- Hotspots detected by c-FIRST.

Tahitian Terrace Residences, Pacific Palisades; lingering hotspots from burned houses.



Eaton Fire Region: Multiple active hotspots mapped in the mountain range, shown via 3.8 μm channel over Google Earth. Lingering hotspots may reignite under favorable winds.

- Numerous lingering hotspots detected by c-FIRST (T >500 K).

Wildfires are becoming increasingly common and increasingly destructive. Monitoring them is challenging; since they burn so hot, and because smoke and wind are often factors, ground- and aircraft-based observations are not always possible. While observation from space is a potential solution, satellites based on traditional technology usually only observe a given location once every few days or weeks. The ideal solution is one that is space based, has high resolution, and revisits the same site multiple times a day.

A promising advance toward that solution is the Compact Fire Infrared Radiance Spectral Tracker (c-FIRST), a space-based detector developed by the University of Hawai'i and JPL as part of the instrument incubation program (IIP) that relies on two MDL-enabled technologies: HOT-BIRDs and digital readout integrated circuits (DROICs). c-FIRST's quarter-sized HOT-BIRD allows the instrument to be small, while its DROIC boosts its dynamic spectral range, increasing the hottest observable targets from 1000 K to 1600 K. With a minimum detectable temperature of 300 K, c-FIRST can detect any terrestrial wildfire. It is also small enough to be launched as part of a SmallSat constellation that would permit the same area to be imaged multiple times per day at high resolution.

Additionally, unlike existing spaceborne infrared sensors, c-FIRST offers ~60 m spatial resolution—far superior to the 750 m resolution of current instruments like the Visible Infrared Imaging Radiometer Suite (VIIRS).

c-FIRST's usefulness was proven during the Eaton and Palisades fires of early 2025. The instrument was flown on NASA's B-200 aircraft and successfully identified hotspots as late as five days after the fires were contained. Its ability to operate at high altitudes (~6,096 m) and capture unsaturated thermal data across a wide dynamic range demonstrates the power of HOT-BIRD technology in real-world applications. These capabilities are critical in post-fire assessment and mitigation, as lingering hot spots can reignite under changing weather conditions.

In the future, the team will incorporate AI to more quickly identify possible burn areas and prioritize those areas for downlinking to first responders. A radiation-resistant computer system will also be developed that will better withstand conditions in space.

c-FIRST's HOT-BIRD was developed with support from the Earth Science Technology Office (ESTO) at NASA, and its DROIC was developed in collaboration with Copious Imaging LLC, with funding from NASA's Small Business Innovation Research (SBIR) program.

MDL-DEVELOPED TECHNOLOGIES HAVE NOT ONLY REVOLUTIONIZED SPACE SCIENCE BUT ALSO ENHANCED LIFE ON EARTH

c-FIRST, designed as a spaceborne instrument, was flight-tested aboard NASA's B200 aircraft in January 2025.

c-FIRST enables scientists to gather data about fires and their impacts on ecosystems with greater accuracy and speed than other instruments.

WATER QUALITY analysis in space

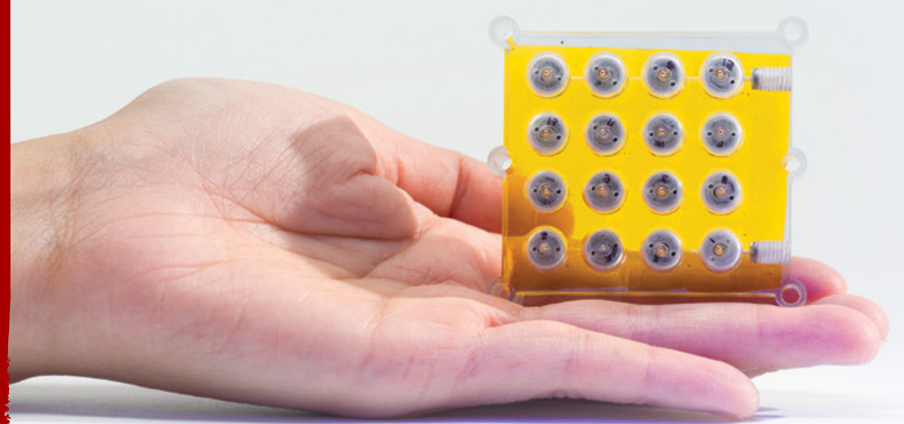
The Inorganic Water Module (IWM) of the Spacecraft Water Impurity Monitor (SWIM) will enable astronauts to analyze water quality in situ on spacecraft and in extraterrestrial habitats.

As NASA prepares for the next generation of human space exploration of the Moon and Mars, many new capabilities will be needed for space exploration vehicles and habitats to ensure the safety of astronauts and the proper functionality of spacecraft systems.

Human space travel requires water. Water is not only critical for human survival but also an essential habitat resource for human space travel, including on the International Space Station (ISS). The ISS is a key research location that facilitates the development and testing of technologies that will enable future human exploration missions beyond low orbit. However, because the ISS and Earth are comparatively close, potable water can be delivered to the ISS during resupply missions and reprocessed samples can be returned to Earth for detailed testing.

All the water onboard ISS, including humidity condensate and urine distillate, is recycled and reprocessed as potable for consumption. Only basic measurements are performed on the ISS; the detailed chemical characterization of stored water samples is conducted in laboratories on Earth upon the return of sample bags.

Image: Array of sensors used to determine some of the bulk properties of the water like, pH and conductivity, as well as concentrations of some inorganic ions, like sodium and calcium.



ASTRONAUTS WILL BE ABLE TO TEST THEIR OWN WATER WITHOUT RELIANCE ON EARTH-BASED ANALYSES

CAPILLARY ELECTROPHORESIS AND CAPACITIVELY COUPLED CONTACTLESS CONDUCTIVITY DETECTION TO ANALYZE WATER QUALITY IN SPACE

As longer-duration missions to the Moon and Mars become a reality, it will no longer be possible to conduct detailed analyses on samples sent back to Earth.

New technologies will be needed to facilitate water characterization onboard future spacecraft and habitats. The SWIM Monitor is being developed to provide in situ analytical capabilities to support NASA's future missions to places where sample return is not feasible like the Moon and Mars. The SWIM system is divided into an Organic Water Module (OWM) and IWM. SWIM takes advantage of established collaborations between the Life Support Systems Branch at the Johnson Space Center and JPL on technologies for environmental monitoring.

The IWM is being developed at MDL by the Chemical Analysis and Life Detection team, and it builds on technology that has been matured by this group over more than 15 years. IWM development is focused on providing onboard capability comparable to the analytical techniques used on returned samples, enabling the detection of a broad range of inorganic compounds at relevant concentrations. Ideally, this detailed chemical characterization would be performed during regular (e.g., weekly) sample assessments, but it also should be available for as-needed analyses in case of anomalies.

A prototype of the IWM was used to test the sequence of operations and validate laboratory analysis protocols.

LASER SENSORS for spacecraft and astronaut safety

Tunable Laser Spectroscopy (TLS) enables compact instruments like the CPM to track CO, CO_2, and O_2 levels on spacecraft—vital for air quality and future resource use on the Moon or Mars.

The Cygnus NG-19 resupply spacecraft arriving at the ISS on August 4, 2023, with the Saffire-VI experiment aboard.

Crewed missions on long-travel vehicles like Orion, as well as the establishment of the Gateway lunar space station, will require reliable sensors to ensure a safe habitat for astronauts during their journey from Earth. TLS is a powerful tool to quickly and accurately monitor gas-phase molecules that are crucial to astronaut health. In recent years, many gas sensors based on mid-infrared lasers have been developed and delivered. The Combustion Product Monitor (CPM) instrument, capable of detecting sub-atmospheric concentrations of CO_2 and O_2 and 5 ppmv of CO, was part of the Spacecraft Fire Safety Demonstration (Saffire) project. The instrument could also detect HF and HCl below the 24-hour spacecraft maximum allowable concentration (SMAC) of 2 ppmv.

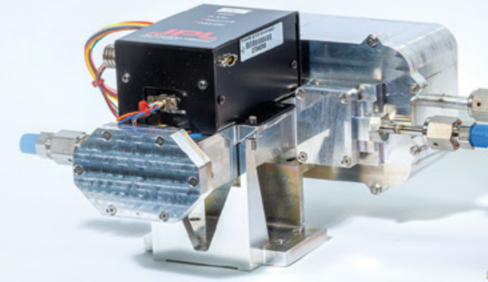
Now, with the use of lithium-ion batteries in modern computers, the early detection of a battery fire incident can help prevent catastrophic consequences for astronauts. A miniaturized version of the CPM instrument was developed at MDL for this goal and measures O_2, CO_2, and CO concentrations in the air every second.

These sensors are critical for the early detection of fire events, and they also allow air monitoring during post-fire cleanup: Once a fire has been mitigated, astronauts need to know when the air inside the cabin is back within health requirements prior to removing any breathing apparatuses.

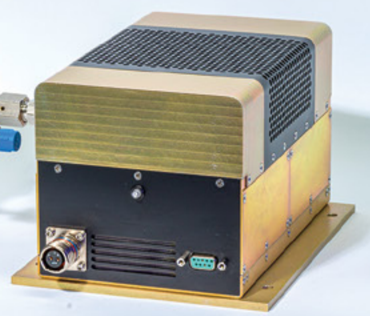
TLS sensors are also very robust and vacuum safe, and they do not suffer from hysteresis, enabling them to function under a wide range of fire mitigation steps, like exposing the area with the fire to vacuum.

Many additional ongoing efforts at JPL involve MDL in the delivery of TLS specifically supporting astronaut safety. These instruments include the portable TLS (PTLS) and the miniaturized TLS (MTLS) as part of the Miniaturized Total Organic Carbon Analyzer (Mini-TOCA). The PTLS is a network of sensors that can monitor O_2, CO_2, and H_2O inside a space station from multiple locations simultaneously, while the MTLS measures the presence of organic matter in water by sensing CO_2 post-oxidation, which is used to determine whether the water supply is drinkable.

These sensors can also be used for the process monitoring of in situ resource utilization (ISRU) systems. Such systems are crucial for the long-term presence of humans on the Moon or Mars and will allow the extraction of needed natural resources, like propellant, in space. MDL has developed and delivered the Laser In-situ Resource Analyzer (LIRA), a sensor capable of measuring sub-parts-per-million levels of water in pure oxygen, a critical measurement because water content must be low prior to propellant liquefaction.

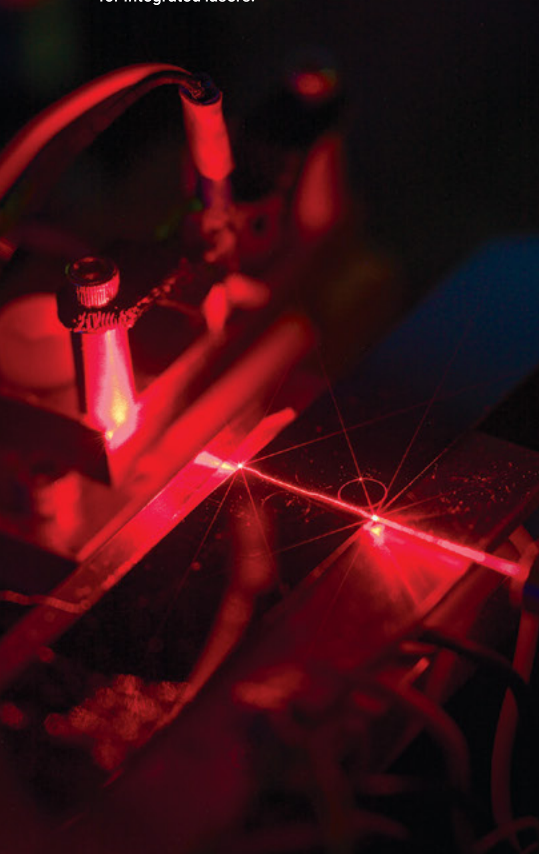


LIRA is a sensor to detect trace water in oxygen propellant streams generated by in situ resource utilization systems operating in a lunar environment.



The CPM instrument was used in NASA's Saffire project to study how fires behave in low-gravity spacecraft environments.

The Miniature CPM is a six-channel tunable laser absorption spectrometer developed by MDL.



Low-loss optical platform for integrated lasers.

Advancing laser technologies for deployable QUANTUM SENSORS

MDL is developing next-generation quantum sensors that can be used in instruments for applications in astrophysics, planetary science, Earth science, and defense.

Atom interferometry exploits the wave-like nature of cold matter to carefully probe the behavior of atoms themselves. Since atoms have nonzero mass, atom interferometry is applicable to areas including precision inertial sensing, gravitational wave detection, and tests of fundamental physics, among others.

Looking forward, instrument concepts such as the Quantum Gravity Gradiometer (QGG) seek to leverage the superb sensitivity of ultracold atoms for the remote sensing of changes in Earth's gravitational field, representing a single-spacecraft approach to gathering mass change data with comparable or better performance than existing dual-spacecraft missions such as the Gravity Recovery and Climate Experiment (GRACE)-Follow On (FO). The ability to make sensitive gravity measurements from a single instrument also opens up possibilities for gravity missions to other solar system bodies, where geological mapping and resource detection may help with site selection for human mission planning, as well as increased temporal and spatial coverage of Earth-based gravity metrology for strategic and defense surveillance and natural disaster forecasting.

However, to date, atom interferometers have operated as bulky laboratory-scale experiments requiring substantial supporting hardware. Translating cold-atom interferometers and other atomic quantum sensors to space-deployable platforms requires a significant leap in supporting technology to reliably achieve the sensitivity needed for future science goals while meeting platform size and power constraints.

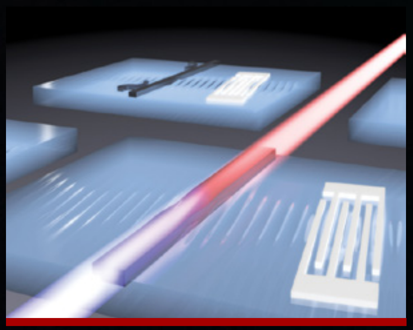
A major driver of resource requirements in these instruments is the need for a sophisticated laser and optics system (LOS) to prepare, cool, manipulate, and probe the atoms. The LOS must operate around the wavelength band of interest (e.g., 780 nm for rubidium [Rb], 852 nm for cesium [Cs]) and deliver an array of rapidly frequency- and intensity-switchable laser beams without injecting excess noise into the atomic physics package and while maintaining long-term stability and reliability.

THESE INNOVATIONS WILL LEAD TO FLIGHT-QUALIFIED, POWER-EFFICIENT LASER SYSTEMS FOR LONG-TERM MISSIONS

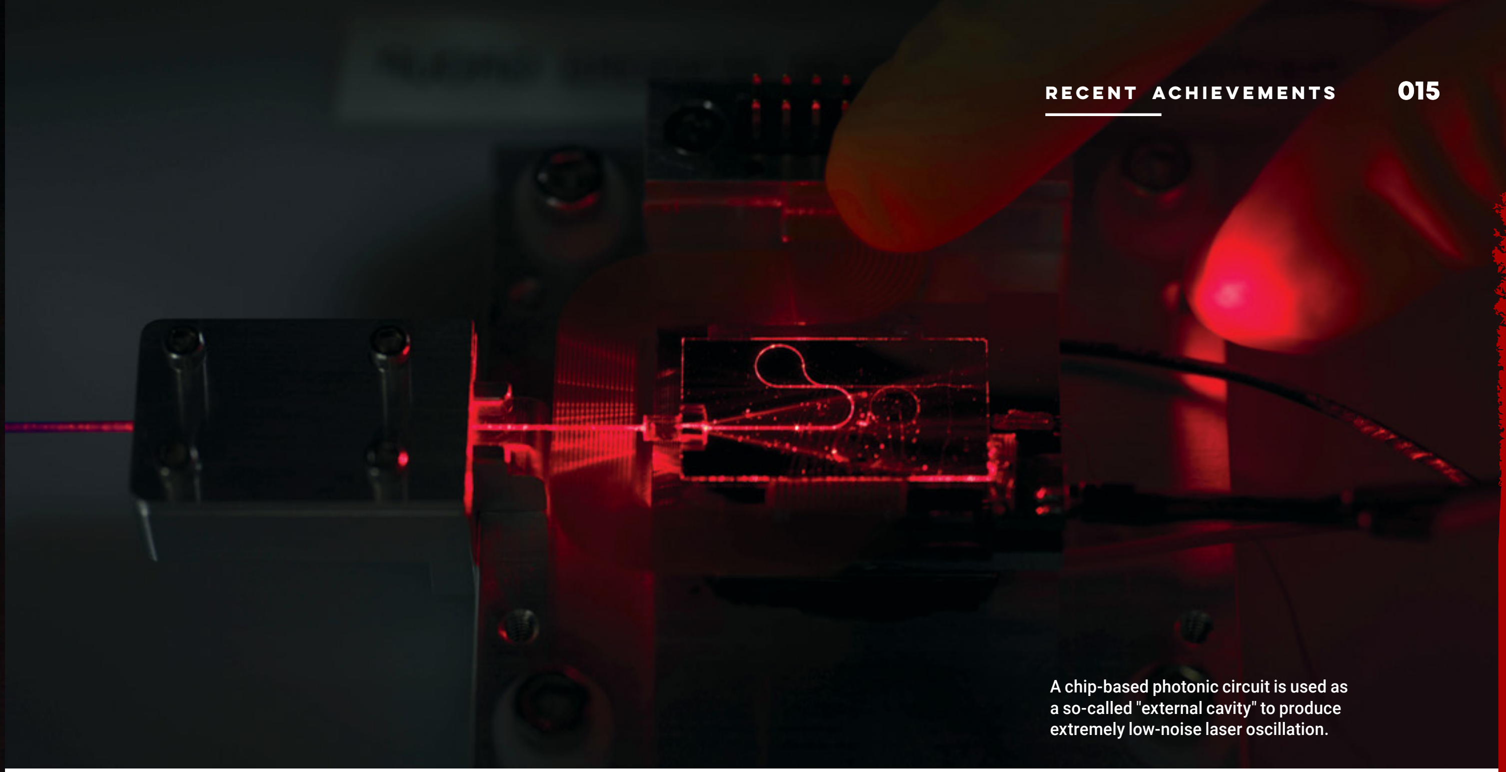
At MDL, researchers are using their deep expertise in photonics, quantum engineering, and space systems, combined with end-to-end capabilities in modeling, semiconductor microfabrication, device packaging, and reliability testing to advance custom photonic technologies to enable next-generation space-qualified quantum instruments. They are building compact, low-power, high-performance photonic subsystems tailored to future quantum sensors that will require components operating at visible and near-infrared wavelengths not widely used in existing commercial applications.

The team works with a multitude of materials and platforms, covering 400 nm to 5 µm. Combined with application-specific electronics design and system integration, this strategy permits a vertically integrated approach for technology validation and maturation to ensure suitability for integration in future flyable instruments.

One recent milestone is the development of a fully integrated, flight-oriented laser system designed for cold-atom operation using Rb or Cs.



Hypersound waves can be used to manipulate the behavior of light guided on the surface of a photonic microchip.



A chip-based photonic circuit is used as a so-called "external cavity" to produce extremely low-noise laser oscillation.

Custom, path-to-flight electronics and packaging facilitate both robust operation and improved efficiency for the laser system.

ONE CUSTOM LASER OPTICS SYSTEM FOR THESE SENSORS CONSUMES LESS THAN 15 W OF POWER AND FITS IN <0.3 SQUARE FEET

The custom LOS replaces upstream optical power amplifiers with low-power seed lasers and semiconductor optical amplifiers (SOAs) directly prior to the system output. This approach negates optical losses through the intermediate optical components and simplifies thermal management. The LOS generates all the optical beams required to cool, trap, and manipulate Cs or Rb atoms, consumes less than 15 W of power, and fits within an footprint of 8x8x6 inches. Low-noise electronics developed in-house are used to control an array of laser amplifiers, offering closed-loop temperature and power stabilization, phase-locking hardware, pulse sequencing and switching, and communication with external devices. Critically, the electronics architecture utilizes radiation-hard and flight-heritage components, and it is modular, so it can be augmented or modified to adapt to different mission needs. Further miniaturization of this prototype, as well as the incorporation of functions such as high-power pulse synthesis and transport beams for interferometry, is ongoing.

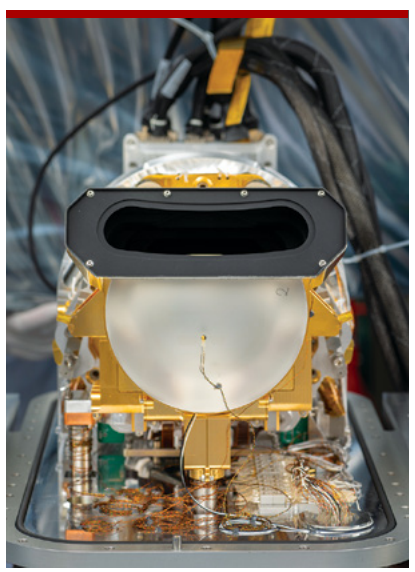
Complementing these system-level advances, the team continues to develop novel photonic components that will help meet the performance requirements of future science-grade quantum instruments. Building on MDL's history of leadership in novel semiconductor laser design and fabrication, the team has demonstrated a sub-kHz linewidth, chip-based external cavity laser at 852 nm tailored to the Cs D2 line.

The superb low noise of this laser architecture will be critical to preserving the fidelity of the atomic system as longer free-evolution times become available in microgravity. In collaboration with external partners for wafer growth, the team is developing in-house fabrication strategies for SOAs that deliver higher optical powers (>100 mW) than do existing commercially available parts, meeting a key requirement for efficient atom splitting in high-contrast interferometry. To further reduce LOS power requirements, MDL researchers are also developing new, chip-based acousto-optic devices that use hypersound waves to efficiently manipulate the intensity and frequency of optical beams with electrical power requirements far lower than those of existing commercial parts.

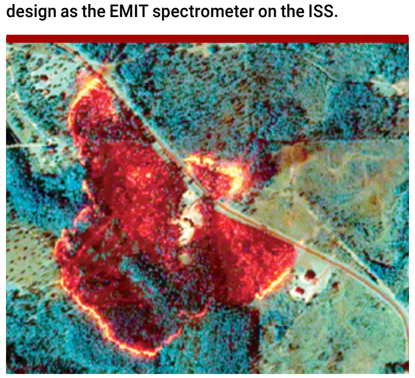
These developments directly address the lack of flight-qualified, power-efficient laser systems suitable for long-duration, remote quantum sensing missions. The modular LOS architecture developed at MDL is reconfigurable and scalable to other laser-based quantum sensors, addressing a critical bottleneck for deploying quantum sensors in space. The simultaneous maturation of key component technologies, such as narrow-linewidth lasers and high-power SOAs at custom wavelengths, will allow the lab to deliver enabling hardware for a broad portfolio of Earth science, planetary, and astrophysics missions.

Real-time remote sensing for WILDFIRES

AVIRIS and the Firesense Airborne Campaign are part of NASA's work to leverage its expertise to combat wildfires using solutions including airborne technologies.



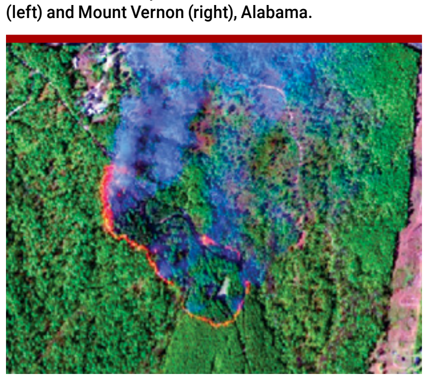
AVIRIS-3 uses a fast (F/1.8) two-mirror telescope and Dyson spectrometer, covering a 40° swath (1240 spatial pixels) across the 380–2500 nm spectrum with 5 nm sampling. It shares the same design as the EMIT spectrometer on the ISS.

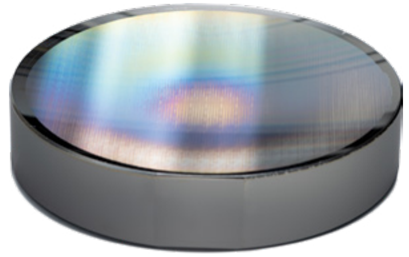


The Airborne Visible Infrared Imaging Spectrometer 3 (AVIRIS-3) sensor has recently demonstrated its effectiveness in wildfire detection and response. On March 19, 2025, while flying over Castleberry, Alabama, AVIRIS-3 identified a 120-acre wildfire that had not yet been reported. Aboard the aircraft, a scientist processed the data in real time, pinpointing the most intense areas of the fire. This information was immediately transmitted to ground crews via satellite internet, enabling firefighters to respond swiftly and contain the blaze before it could spread farther. During its deployment in March 2025, AVIRIS-3 mapped at least 13 wildfires and prescribed burns across Alabama, Mississippi, Florida, and Texas. Its rapid data processing and dissemination capabilities have proven invaluable in enhancing situational awareness and improving the efficiency of wildfire response efforts.

The AVIRIS-3 sensor belongs to a line of imaging spectrometers built at JPL since 1986. The instruments have been used to study a wide range of phenomena, including fire, by measuring sunlight reflecting from the planet's surface. Data from imaging spectrometers like AVIRIS-3 typically take days or weeks to be processed into highly detailed, multilayer image products used for research. By simplifying the calibration algorithms, researchers were able to process data on a computer aboard the plane in a sliver of the time it otherwise would have taken, and airborne satellite internet connectivity enabled the images to be distributed almost immediately, while the plane was still in flight, rather than after it landed.

Below: AVIRIS-3 captures wildfire data near Perdido (left) and Mount Vernon (right), Alabama.





AVIRIS-3 is the third of the AVIRIS spectrometer series and has been developed in parallel with the Compact Wide-swath Imaging Spectrometer II (CWIS-II) with the University of Zurich, Switzerland. The core spectrometer of AVIRIS-3 is a copy of the optically fast, F/1.8 Dyson imaging spectrometer used by the Earth Surface Mineral Dust Source Investigation (EMIT) that is currently operating on the ISS.

AVIRIS-3 is intended to provide state-of-the-art imaging spectroscopy measurements for NASA's science and application programs through the next decade and beyond. AVIRIS-3 uses the EMIT spectrometer design interfaced with a scaled two-mirror telescope enclosed in a compact vacuum vessel to enable measurements from airborne platforms.

At the heart of these instruments are unique and finely optimized components developed at MDL. The gratings, slits, and stray light traps are the result of more than a decade of MDL development and refinement, as well as use and testing in previous imaging spectrometers such as Hyperion, CRISM, M3, AVIRIS, and others.

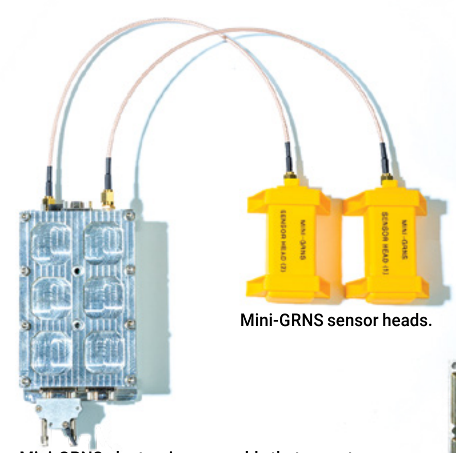
From Earth's own atmosphere to the farthest reaches of the known universe, the insights that NASA has gathered from robust observations are often facilitated by the custom components created via e-beam fabrication at MDL. MDL's e-beam capabilities fulfill an important role for JPL and NASA by providing unique components that are not available from commercial suppliers, and its fingerprints are on myriad missions.

DATA FROM THE AVIRIS-3 SENSOR WAS RECENTLY USED TO CREATE DETAILED FIRE MAPS IN MINUTES, ENABLING FIREFIGHTERS IN ALABAMA TO LIMIT THE SPREAD OF WILDFIRES AND SAVE BUILDINGS

COMPACT gamma-ray and neutron sensor

JPL is developing the mini-GRNS, a compact gamma-ray and neutron spectrometer to detect subsurface water and elemental composition on planetary missions. Its low power and small size make it ideal for lightweight platforms like Mars helicopters. This dual-mode sensor supports NASA's goals for efficient, versatile lunar and Martian exploration.

Prototype sensor head used for mini-GRNS electronics development at Dynamitron laboratory.



Mini-GRNS sensor heads.

Mini-GRNS electronics assembly that operates two sensor head modules. 124x71x39mm, 302g total weight.

A SCALABLE SOLUTION FOR APPLICATIONS ON EARTH AND OTHER WORLDS

Significant progress is underway on a miniaturized gamma-ray and neutron spectrometer (mini-GRNS), a next-generation instrument engineered to measure the subsurface water content and elemental composition of planetary bodies. Initially developed for future Mars helicopter missions, it is compact and combines low mass, low power consumption, and dual-mode sensing in a single, efficient package.

The mini-GRNS will utilize two lightweight sensor heads, each approximately 300 g, combining a scintillation crystal with a photomultiplier tube in a tightly integrated system. These sensors can detect both thermal and epithermal neutrons to estimate hydration levels in planetary regolith, measuring water content ranging from 1% to 8% by weight. Additionally, the same sensor heads can detect gamma rays, which can reveal the presence of elements such as silicon (Si), aluminum (Al), and thorium (Th) by measuring their unique energy signatures.

Electronics and mechanical chassis designs, along with structural analysis, are complete. Sensor head fabrication is scheduled for 2026, with a goal of reaching Technology Readiness Level (TRL) 5 by year's end. The electronic system features two ultra-low-power pulse shape discrimination (PSD) circuits and a field programmable gate array (FPGA) board for instrument control. These innovations have already demonstrated more than 70% power savings compared to prior spectrometers like the LunaH-Map neutron spectrometer, bringing the power requirement down to 3 W for a two-head configuration—well below the previous ~10 W.

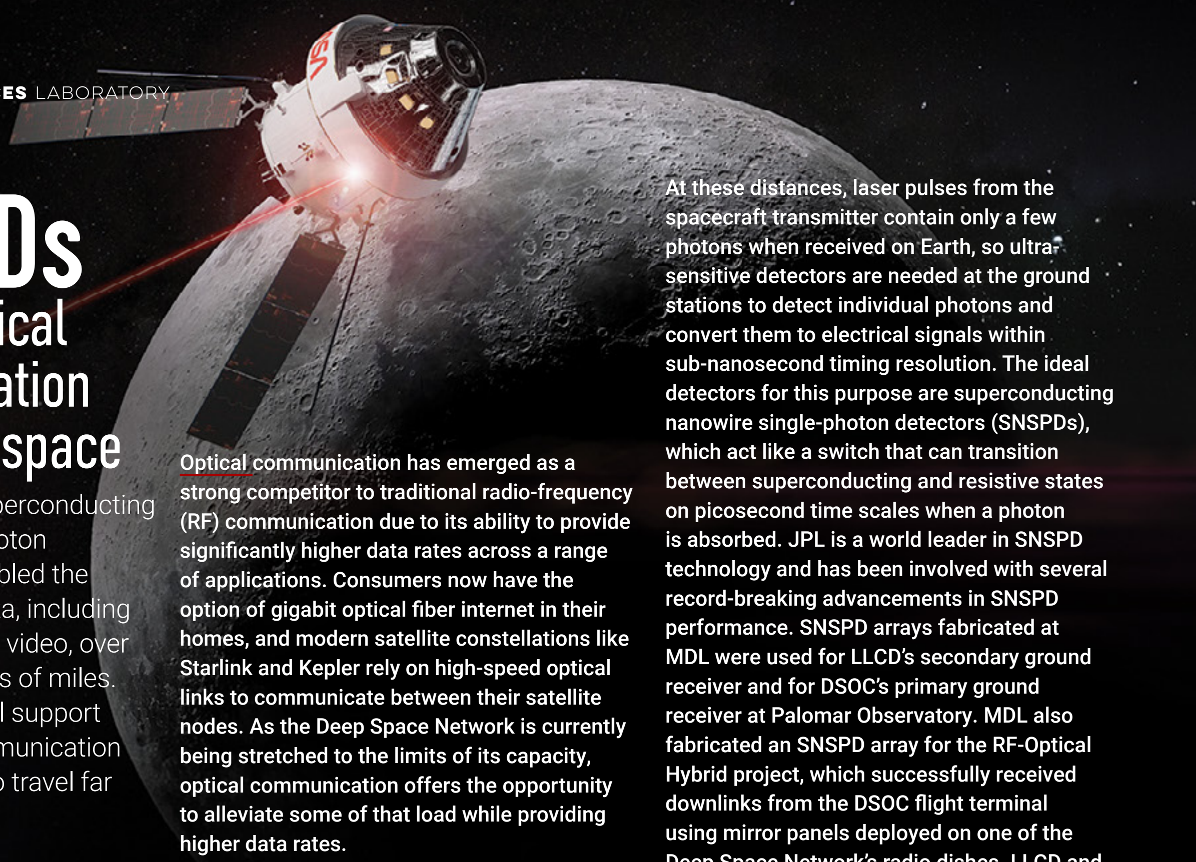
A promising feature of the mini-GRNS is its ability to detect both neutrons and gamma rays with one scintillator material (Cs_2LiYCl_6:Ce, or CLYC). This dual capability sets it apart from previous spectrometer designs, which typically require separate sensors for each particle type. This advancement builds on the successful spaceflight heritage of the Mini-Neutron Spectrometer flown aboard the Artemis CubeSat LunaH-Map mission.

The current effort is a collaboration among JPL, Arizona State University, and Radiation Monitoring Devices, which supplies the scintillator crystals. While the mini-GRNS is being developed under NASA's Strategic Technology Research and Development program, interest in the technology has expanded beyond NASA. Other government agencies, such as the Department of Defense and the Department of Energy, have expressed interest in the instrument for its potential applications in national security and environmental monitoring.

The mini-GRNS platform is scalable: While the current design is optimized for low-mass platforms like Mars helicopters, it can be adapted with larger crystals for use on lunar rovers, landers, or astronaut-deployed instruments. Work is also underway to explore modifications to turn the GRNS into a compact imaging system, pending successful prototype demonstrations and future funding.

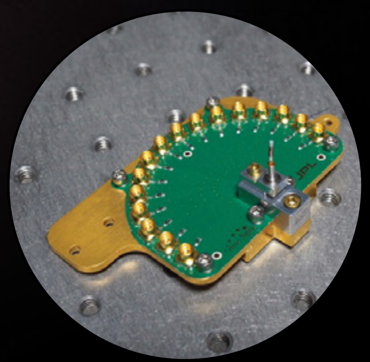
By merging compact design with advanced sensing capabilities, the mini-GRNS represents a transformative step toward versatile, efficient planetary science instruments that support NASA's long-term goals of lunar and Martian exploration.

Miniaturization is a key contribution from MDL. The new electronics and chassis were designed, fabricated, assembled, and tested at MDL, resulting in a ~70% reduction in both power and mass compared to the previous state-of-the-art instrument.



SNSPDs enable optical communication from deep space

MDL-developed superconducting nanowire single-photon detectors have enabled the transmission of data, including ultra-high-definition video, over hundreds of millions of miles. This technology will support long-distance communication as humans begin to travel far beyond Earth.



Two of the White Sands O2O arrays being screened at JPL.

DSOC AND EUROPA CLIPPER NAMED IN TIME'S BEST INVENTIONS OF 2024

Optical communication has emerged as a strong competitor to traditional radio-frequency (RF) communication due to its ability to provide significantly higher data rates across a range of applications. Consumers now have the option of gigabit optical fiber internet in their homes, and modern satellite constellations like Starlink and Kepler rely on high-speed optical links to communicate between their satellite nodes. As the Deep Space Network is currently being stretched to the limits of its capacity, optical communication offers the opportunity to alleviate some of that load while providing higher data rates.

Future space missions are expected to produce increasingly large volumes of data, whether from science instruments like imaging spectrometers or from video cameras and life-support systems on a crewed spacecraft. While optical communication may be the only way to achieve the necessary data rates for these missions, space-to-ground optical communication at lunar and interplanetary distances is not a well-established technology. At these distances, the signals received at ground stations are too faint to use typical optical encoding schemes, so data are instead encoded in the timing of laser pulses. The Lunar Laser Communication Demonstration (LLCD) was the first demonstration of high-photon efficiency (HPE) optical communication from lunar distances, achieving a data rate of 622 Mbps as part of the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission in 2013. Recently, the Deep Space Optical Communications (DSOC) demonstration on board the Psyche spacecraft achieved data rates of 267 Mbps from Mars-near range and 50 Mbps from Mars-average range—an improvement of 10 to 100 times over existing RF capabilities at Mars.

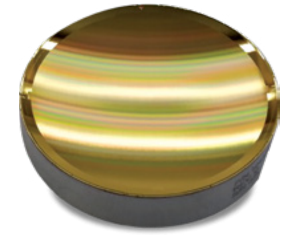
DSOC is the first demonstration of free-space laser communication from interplanetary space and increased the record for longest-range optical communication by over a factor of 1000. It exceeded its baseline requirements and beat its estimated link budget by approximately a factor of two.

At these distances, laser pulses from the spacecraft transmitter contain only a few photons when received on Earth, so ultra-sensitive detectors are needed at the ground stations to detect individual photons and convert them to electrical signals within sub-nanosecond timing resolution. The ideal detectors for this purpose are superconducting nanowire single-photon detectors (SNSPDs), which act like a switch that can transition between superconducting and resistive states on picosecond time scales when a photon is absorbed. JPL is a world leader in SNSPD technology and has been involved with several record-breaking advancements in SNSPD performance. SNSPD arrays fabricated at MDL were used for LLCD's secondary ground receiver and for DSOC's primary ground receiver at Palomar Observatory. MDL also fabricated an SNSPD array for the RF-Optical Hybrid project, which successfully received downlinks from the DSOC flight terminal using mirror panels deployed on one of the Deep Space Network's radio dishes. LLCD and DSOC were technology demonstrations, so the team sent their own telemetry and data files (including DSOC's viral video of a cat named Taters www.jpl.nasa.gov/news/nasas-tech-demo-streams-first-video-from-deep-space-via-laser/) instead of LADEE and Psyche mission data over the optical link. The first operational HPE optical communication system will be the Orion Artemis II Optical Communications System, or O2O. The flight transceiver for O2O will launch onboard the Orion capsule as part of the second Artemis mission to the Moon. O2O has two primary ground stations, located at White Sands, New Mexico, and at JPL's Table Mountain Facility (TMF) in California.

MDL fabricated four fiber-coupled SNSPD arrays for the White Sands terminal as a subcontractor to local company Photon Spot, Inc. MDL also fabricated a 64-channel array for the JPL-managed TMF ground station based on the DSOC array design. The detector arrays will be used to achieve downlink data rates up to 260 Mbps, enabling the transfer of high-definition video, as well as telemetry and mission data from the Orion capsule. A successful O2O demonstration will pave the way for the future adoption of optical communications, validating key technologies for high-bandwidth data transfer from space. In total, MDL has delivered five superconducting detector instruments to telescopes for NASA optical communication ground terminals. This unique MDL capability has been a core component of these missions' success.

Searching for signs of life on EUROPA

Europa Clipper will reach Jupiter by 2030; once there, its Mapping Instrument Spectrometer for Europa will analyze Europa's surface and help determine whether the conditions there are compatible with life. The results will inform decisions on future missions and determine the habitability of this moon.



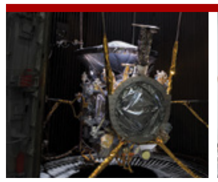
Concave grating for MISE.

BY COMBINING ENGINEERING INNOVATION AND DEEP SPACE SCIENCE, THE EUROPA CLIPPER MISSION REPRESENTS A MAJOR STEP FORWARD IN HUMANITY'S SEARCH FOR LIFE BEYOND EARTH

Europa, one of Jupiter's largest moons, is one of the most promising candidates for harboring life beyond Earth. Beneath its icy crust lies a vast subsurface ocean—possibly containing more water than all of Earth's oceans combined—where scientists believe conditions may support life.

NASA's Europa Clipper spacecraft, launched in October 2024, is the agency's most ambitious mission to an ocean world. The largest NASA spacecraft ever sent to another planet, it has solar panels spanning the length of a basketball court and will reach Jupiter by 2030. Once in orbit, it will perform 49 close flybys of Europa to study the moon's surface and subsurface features in unprecedented detail.

Among Europa Clipper's nine science instruments is the Mapping Imaging Spectrometer for Europa (MISE), designed to investigate the moon's surface chemistry. MISE will detect and map organic materials, salts, and other compounds and compare them to those found in Earth's oceans. While the mission is not intended to detect life directly, it aims to determine whether



Europa Clipper prepares for test in space simulator.

MISE with MDL- developed components.

Europa's environment has the necessary ingredients—such as liquid water, key chemical elements, and internal heat sources—to support it. MDL played a critical role in MISE by fabricating its diffraction grating, slit, and zero-order light trap.

Europa Clipper's primary science goals include determining the thickness of the moon's icy shell, studying the ocean's interaction with the surface, analyzing geological activity, and identifying potential landing sites for future missions. These objectives will help assess Europa's potential habitability and expand our understanding of ocean worlds across the solar system.

The Europa Clipper mission is led by JPL in partnership with the Johns Hopkins Applied Physics Laboratory and other NASA centers. The spacecraft is also carrying a range of advanced technologies, including optical communication systems and innovative deployable structures, developed and funded by various NASA programs focused on small spacecraft and game-changing technologies.

Assessing CMOS performance in mission conditions

Space-based instruments are constantly bombarded by high-energy particles, which can substantially degrade instrument performance. MDL quantified this degradation by developing a new apparatus to irradiate pairs of CMOS sensors at room temperature and at colder temperatures more representative of space. The findings will shape future instrument testing paradigms.

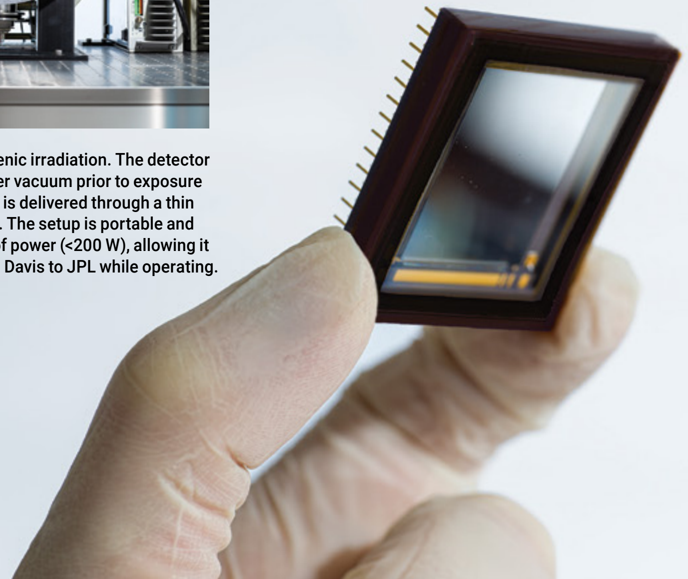
Apparatus used for cryogenic irradiation. The detector is cooled (203 K) and under vacuum prior to exposure to the proton beam, which is delivered through a thin (2 mm) aluminum window. The setup is portable and consumes a low amount of power (<200 W), allowing it to be transported from UC Davis to JPL while operating.

Highly sensitive instruments must be accurate in their operational environment. In space, sensitive detectors are vulnerable to damage from particles trapped in Earth's magnetic field, high-energy solar protons, and galactic cosmic rays, which all steadily degrade detector imaging capabilities throughout a mission.

Performance loss is a result of the interaction between these energetic particles and the lattice of the sensor. When a particle interacts with a lattice site, it may displace it from its original location to create a vacancy-interstitial pair (Frenkel pair). The vast majority (≥90%) of vacancy-interstitial pairs recombine shortly after production, but the remainder migrate through the lattice until they form stable defects with other impurities. These defects can have energy levels within the bandgap and degrade performance through increased dark current, dark defect / hot pixel formation, random telegraph noise, and charge traps.

The ability of a defect to move through the lattice i.e., "mobility" is highly temperature dependent; therefore, the temperature at which a device is irradiated is intrinsically linked to the final distribution of defects i.e., "defect landscape" and the measured performance at a representative mission-like dose.

Consequently, when a sensor is tested, the most accurate performance estimate will come from irradiating it at the nominal operating temperature of the mission. For silicon-detector-based instruments, this typically means performing the irradiation at <200 K.



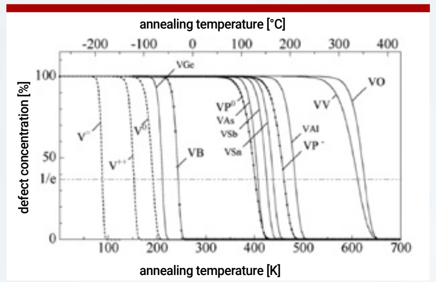
These "cryogenic irradiations" offer a highly accurate performance estimate but are significantly more challenging than equivalent tests at ambient temperatures.

Recently, MDL technologists undertook a vital technology development activity: They performed cryogenic irradiations on large-format, low-noise, delta-doped scientific complementary metal oxide semiconductor (CMOS) image sensors. They designed and successfully deployed a specialized experimental apparatus at the University of California, Davis proton beam. There, the detectors underwent a mission-like dose at both room temperature (~298 K) and 203 K, forming a crucial basis for subsequent performance comparisons. The cryogenically irradiated detector was transported cold and operating back to JPL, where it was monitored for months to assess natural damage repair, a process known as annealing.

The detector tested cold exhibited significantly higher dark current and signal loss than its room-temperature counterpart, demonstrating the importance of cryogenic irradiation for the qualification of high-performance imaging systems. This work is a pivotal advancement in JPL's detector qualification capabilities. It is also highly relevant to detector development for the Habitable Worlds Observatory, which will require large-format, low-noise CMOS detectors such as those tested in this study.

MDL HAS DEVELOPED A SYSTEM TO TEST PERFORMANCE UNDER MISSION CONDITIONS

Schematic representation of vacancy and vacancy-defect pair annealing, taken from 1. Here, 'V' indicates vacancy with the appropriate charge state, and other labels follow the standard periodic table convention. 1. M. Moll, "Radiation damage in silicon detectors," 1984.



Mapping minerals, water, and ice on the MOON

The Ultra-Compact Imaging Spectrometer for the Moon (UCIS-Moon) was selected to fly on a future lunar orbiter where it will provide the highest spatial resolution maps ever collected of water, ice, and minerals on the lunar surface.

In the next decade, NASA and industry partners plan to send dozens of robotic and crewed missions to the lunar surface, with a long-term goal to establish a sustained human presence on the Moon. To achieve this bold vision, it will be critical to understand the resources that are already there. It will be especially important to know the location, amounts, and type of water locked in lunar rocks and stored as ice in permanently shadowed regions at the frigid poles, as well as any mineral resources that might be mined for their iron or other critical elements.

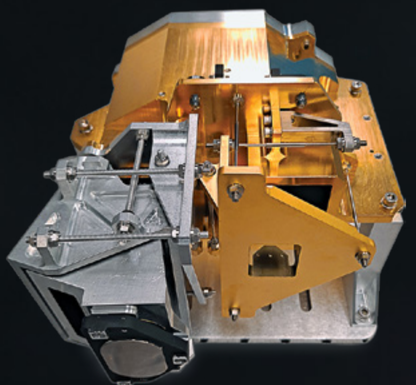
UCIS-Moon was recently selected by NASA for a flight on a future lunar orbiter. UCIS-Moon measures reflected and emitted radiance from the lunar surface between 0.6 and 3.6 μm at 10 nm spectral sampling; it will provide the highest spatial resolution maps ever collected of water, ice, and minerals on the lunar surface. These data will teach us fundamental science about the lunar water cycle and produce critical products for planning future missions to the Moon. They will reveal where the most accessible and abundant ice deposits are, guiding locations for potential human bases. They will document the diverse minerals on the Moon, serving as guides for robotic landers, rovers, and astronauts to visit the most scientifically compelling locations. They will also inform potential lunar prospecting companies about the locations of the most economically viable deposits.

UCIS-Moon is a sister to the High-resolution Volatiles and Minerals Moon Mapper (HVM3) that flew on the Lunar Trailblazer mission.

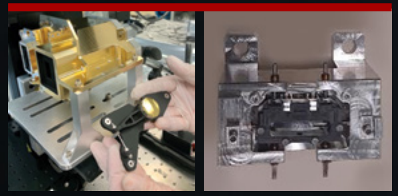
ULTRA-COMPACT SPECTROSCOPY'S NEXT STOP IS THE MOON

UCIS-Moon was originally developed for a lunar lander or rover, but the two instruments share a common spectrometer design and performance specifications. UCIS-Moon adapted for orbit will utilize most aspects of the HVM3 design.

An MDL grating, slit, and light trap are at the heart of the instrument and enable exquisite performance through the wavelength region critical for mapping even the smallest and darkest ice deposits. Like HVM3, UCIS-Moon will be able to detect as little as 100 ppm water ice in permanently shadowed regions at the lunar poles; these regions are illuminated only by scattered light. UCIS-Moon will provide an unprecedented look into these mysterious and critical regions of the Moon.



UCIS-Moon optomechanical hardware assembly with telescope.



Grating and slit shown before installation.

MDL ENABLED UCIS-MOON BY USING ITS E-BEAM TECHNOLOGY TO FABRICATE THE INSTRUMENT'S GRATINGS AND SLITS

MKID array for passive, polarization-sensitive imaging at 150 GHz

MDL has long contributed to the evolving ecosystem of national security and space innovation, supporting agencies such as the Department of Defense, Defense Advanced Research Projects Agency (DARPA), Office of Naval Research (ONR), National Oceanic and Atmospheric Administration, and their predecessors like the Strategic Defense Initiative Organization and the Missile Defense Agency.

Its work in advanced micro- and nano-scale technologies—including radiation-hardened electronics, infrared sensors, and focal plane arrays—has enabled both defense and NASA missions.

MDL's collaborations span areas like machine learning, autonomous systems, and resilient electronics, reflecting its decades-long role in shaping dual-use technologies for emerging strategic priorities.

MDL'S DUAL-USE FOCUS

DEFENSE

High-sensitivity MgB_2 sensors that work at high temperatures

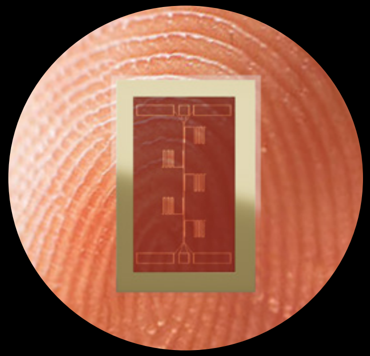
MDL researchers produced wafer-scale magnesium diboride (MgB_2) films for superconducting devices like kinetic inductance and single-photon detectors. MgB_2 promises highly sensitive detectors with reduced cooling needs.

MgB_2 diboride is a well-behaved metallic superconductor with a transition temperature near 40 K. Unlike more traditional high-temperature superconductors, such as yttrium-barium-copper-oxygen (YBCO), it can be readily fabricated to make high-yield superconducting sensors and electronics. Developing superconducting sensors with an operating temperature of 4–20 K will dramatically reduce the size, weight, and power of superconducting detector instruments, as it allows integration with much more compact, simpler cryogenics.

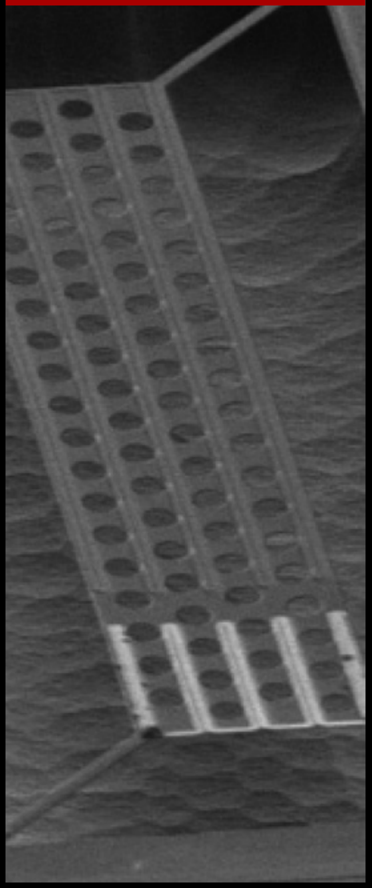
Over the past decade, MDL has been investing in MgB_2 material development technology for a variety of different sensor types, including hot-electron-bolometer mixers for terahertz spectroscopy, SNSPDs for time-resolved single-photon counting, and thermal kinetic inductance detector (TKID) bolometers for millimeter-wave imaging and spectroscopy. MDL has recently developed and patented a thin-film deposition process for MgB_2 that allows the wafer-scale deposition of smooth, high-quality films on 4-inch and 6-inch substrates, a major breakthrough for the field.

Following on this remarkable advance in thin-film deposition techniques, DARPA has awarded JPL a four-year project to advance MgB_2 material properties and demonstrate the feasibility of SNSPDs operating at high temperatures. This high-risk, high-reward project offers the possibility of space flight SNSPD instruments that can be flown at a fraction of the cost of traditional low-temperature detectors.

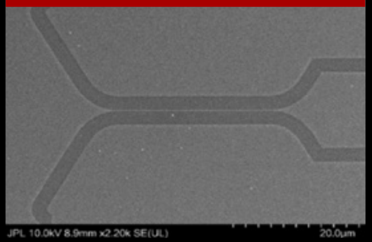
MDL has also demonstrated MgB_2 TKIDs for the first time, which offer the prospect of kilopixel arrays of far-infrared imagers with a sensitivity that far outmatches conventional microbolometers at a much more practical operating temperature than pair-breaking MKIDs.



Optical image of a resonator chip on the Si substrate. MgB_2 film is denoted by the red area.

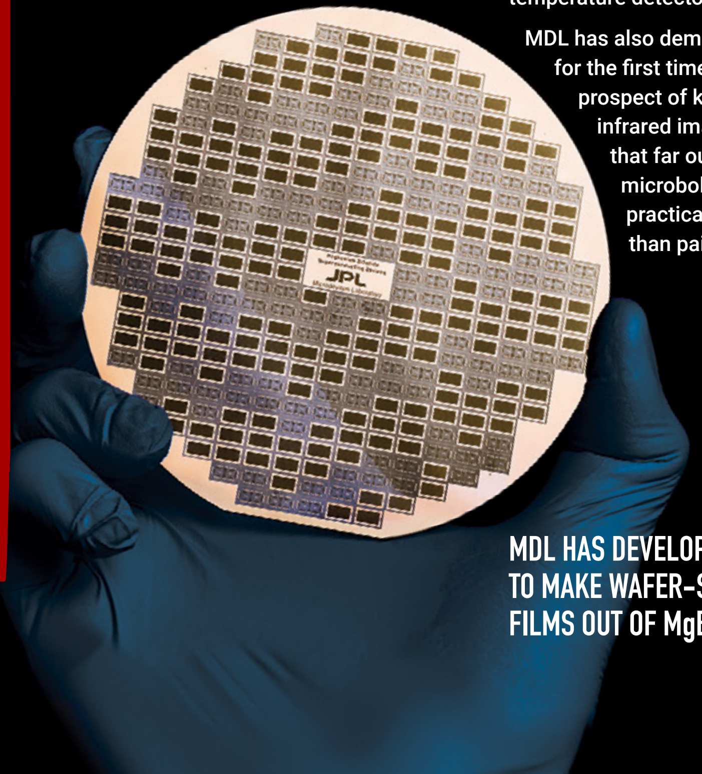


SEM image of a released bolometer. The bright lines on the bottom are a gold trace that is used as an embedded heater.



SEM of nanowires fabricated from MgB_2 films at MDL.

Wafer-scale MgB_2 superconducting device demonstration. Coplanar waveguide microwave resonators and other test chips patterned in MgB_2 film deposited on 100 mm sapphire substrate.



MDL HAS DEVELOPED A METHOD TO MAKE WAFER-SCALE THIN FILMS OUT OF MgB_2

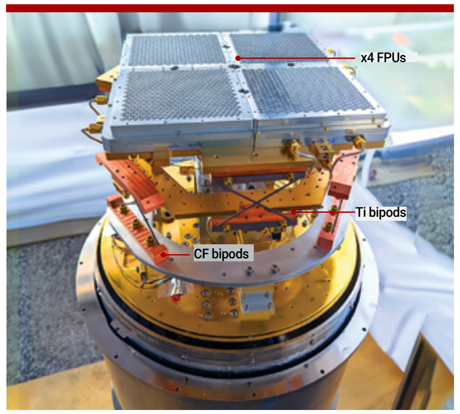
Seeing through fog with MDL-invented MKIDs

ONR turned to Caltech and JPL to improve vision in poor weather using MDL's KID arrays. These detectors enable passive imaging at millimeter wavelengths that penetrate fog. The same technology also boosts sensitivity for cosmic microwave background instruments.

The superconducting kinetic inductance passive radiometer telescope.

The millimeter-wave region of the electromagnetic spectrum is optimal for many applications that require imaging faint thermal signals over a broad range of atmospheric conditions. Diffraction severely limits angular resolution at longer wavelengths, while attenuation in water vapor often prevents the use of shorter wavelengths. However, a remote sensing millimeter-wave instrument that is optimized to be limited only by photon noise from the ambient background can achieve passive imaging through thick optical obscurants.

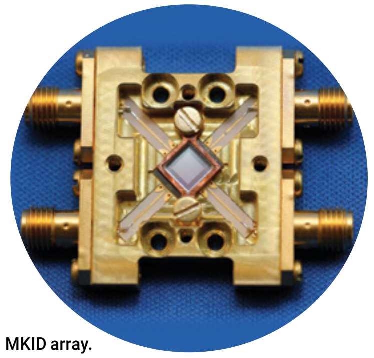
MDL has been developing microwave kinetic inductance detectors (MKIDs) that offer this exact capability. A project sponsored by the ONR with significant JPL involvement and led by a Caltech principal investigator has developed a telescope that is currently deployed at JPL for demonstrating a polarization-sensitive 4 kilopixel MKID FPA. In optical visibilities of tens of meters, the imager can detect millikelvin temperature differences at a range of a few kilometers and at a 30 Hz frame rate, meaning that even though the millimeter-wave signal is attenuated by 20 dB in such conditions, a 1 K temperature difference can be imaged in real time. Deploying this instrument in a marine environment would improve its capability.



The four focal plane units in the SKIPR telescope provide both vertical and horizontal polarization selectivity detectors at each spatial pixel.

The ocean reflects the cold sky, further enhancing thermal contrast. In addition, the reflection is polarized, offering enhanced detection when adding polarization sensitivity. The ONR-sponsored telescope, the Superconducting Kinetic Inductance Passive Radiometer (SKIPR), is a custom-built 1.59 m diameter crossed Dragone telescope with an altitude/azimuth (alt/az) mount to provide 5 feet angular resolution over a 3.5° field of view. Each spatial pixel on the FPA contains two co-located detectors, thereby offering both vertical and horizontal polarization selectivity. The current iteration of the FPA passes the 150 GHz signal within a 30% fractional bandwidth to the FPA through an array of feedhorns, with the photosensitive elements coupled to the feedhorn via a circular waveguide.

Future iterations will use planar phased antenna arrays to provide four-band imaging from 90 GHz to 270 GHz while eliminating the horn arrays and providing fabrication solely via photolithography. These multi-band arrays will also allow for image processing that optimizes between atmospheric transmission at longer wavelengths and diffraction-limited angular resolution at shorter wavelengths. The new FPA, consisting of four individual tiles and a total of 10,000 MKIDs, will be fabricated at MDL and installed as a drop-in replacement for the existing horn-coupled FPA. The detectors are read out using a novel integrated radiofrequency System-On-Chip (RFSOC). The cryostat and readout are controlled by a flexible and easy-to-use firmware and software package developed with significant contributions from collaborators at Arizona State University. The optics required for the upcoming broadband operation are being developed by collaborators at the University of Virginia.

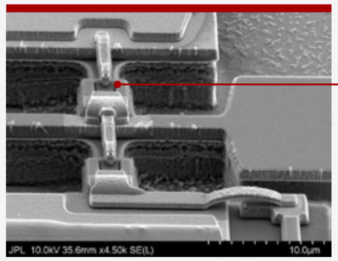


MKID array.

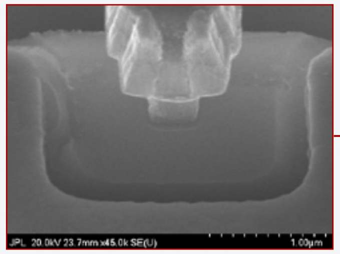
SKIPR WAS DEVELOPED BY THE DESIRE TO OBTAIN PASSIVE IMAGING THROUGH OPTICAL OBSCURANTS

Submillimeter-wave RADAR

PBL has a profound influence on the weather on Earth's surface. MDL's investment into research on differential absorption radar is helping answer critical questions about how the PBL affects cloud cover and rainfall.



2 THz subharmonic mixer device fabricated at MDL.



T-shaped Schottky diode.

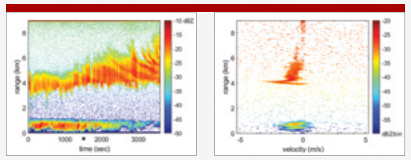
THE NEWEST TERAHERTZ HETERODYNE INSTRUMENT WILL UNCOVER INFORMATION ABOUT A CRITICAL PART OF EARTH'S ATMOSPHERE

Earth's planetary boundary layer (PBL) is at the heart of fundamental science challenges, such as reducing uncertainty in cloud-climate feedback; understanding the sensitivity of extreme weather to a warming world; quantifying the exchanges of energy, water, and carbon between the free atmosphere and the ocean/land surface; and improving forecasts of near-surface air quality. In the last decade, differential absorption radar (DAR) has emerged as a compelling remote sensing technique for mapping vertical distributions of water vapor inside clouds.

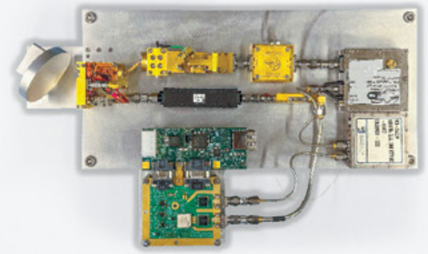
JPL pioneered DAR, which relies on advanced millimeter-wave radar technology. However, to be competitive for consideration in a future space mission, the added capabilities of lower on-board oscillator noise, the development of high-power coherent sources, receiver immunity to higher transmit power, and better along-track spatial resolution are critical for the application of this method on a global basis.

The most recent focus of MDL's investigation into DAR has been to demonstrate more than 400 mW of output power from a compact solid-state source at 240 GHz. MDL researchers have developed a novel on-chip power combining and multiplying capability and have now demonstrated the design and measurement results of an eight-way frequency-tripling power-combined Schottky diode source that produces more than 400 mW of continuous-wave (CW) power at 240 GHz.

This achievement relies in part on two innovations in the circuit. First, the JPL-patented on-chip power uses technology that combines two multiplier structures in a single chip, thus doubling the power handling capabilities (and power output) over traditional designs.



Left: Example of a one-hour cloud curtain measurement captured using the G-band radar. Right: Corresponding range-Doppler map averaged over 100 frames, taken at 1622 seconds (marked by * in the left panel).



MDL'S SUBMILLIMETER WAVE ADVANCED TECHNOLOGIES RESEARCH HAS ENABLED SCIENCE MISSIONS FOR DECADES

Second, the circuit uses a compact and power-efficient architecture that drives four of these chips using four in-phase 80 GHz amplifiers in parallel. This topology avoids unnecessary power-combining and splitting in the W-band input stage, as would be necessary if a conventional single-output amplifier were used to drive the tripler. The room temperature output power measures >400 mW at close to 240 GHz, as desired.

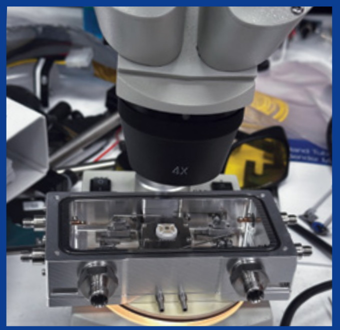
Following its benchtop characterization, the quad-block frequency tripler was integrated into CloudCube's G-band radar electronics in preparation for a one-year field deployment of the radar at the Kennaook/Cape Grim, Tasmania, Baseline Air Pollution Station operated by the Australian Bureau of Meteorology. The deployment was part of the US Department of Energy's CAPE-k campaign to study aerosol-cloud-precipitation interactions in the pristine air of the Southern Ocean. To date, the CloudCube G-band radar has operated continuously 24 hours a day for many months, excluding rare and brief occasions of planned and unplanned site-wide power outages.

In this time, no repairs to the radar have been made, and its sensitivity has not detectably changed. The measured results from this remote deployment provide the first-ever measurement of cloud precipitation at these frequencies. The results bode well for the future deployment of such instruments in space to provide global measurements.

MDL has recently been selected by DARPA to continue its investigation into high power sources. MDL researchers intend to develop power combined sources in the submillimeter-wave with close to 1 W of output power.

MEMS Pressure sensors of the future

MDL's expertise in microelectromechanical systems has enabled the development of pressure sensors that use a simple, direct method to monitor pressure in real time.



A next-generation MEMS-based pressure sensor designed for extreme environments.

THE SENSORS CAN OPERATE AT UP TO 800°C WITH HIGH SENSITIVITY AND BROAD DYNAMIC RANGE

JPL, in collaboration with Georgia Tech, UCLA, and UCSB, is developing next-generation microelectromechanical systems (MEMS)-based pressure sensors designed for extreme environments. These sensors operate at temperatures up to 800°C, offer dynamic ranges of 90 dB, and support bandwidths of over 1 MHz, breaking long-standing limitations in high-temperature pressure sensing and enabling real-time measurements for aerospace, energy, and planetary science applications.

Unlike conventional pressure sensors, which rely on the deflection of a membrane, MEMS-based sensors function as resonant micromechanical devices with modal frequencies in the MHz range. Pressure changes induce shifts in resonant frequency, delivering high sensitivity and broad dynamic range.

MDL has developed a high-dynamic-range platform to capture these signals at elevated temperatures. This data acquisition system tracks resonance behavior under demanding conditions. The team also introduced a novel testing method that improves upon conventional calibration in both fidelity and efficiency. For the first time, direct high-speed dynamic pressure measurements above 1 MHz in extreme conditions have been experimentally demonstrated.

A key innovation is the use of a frequency-doubled Nd:YAG laser (1–2 ns pulse duration, 650 mJ/pulse) to generate a laser-induced spark in air. The expanding spark forms a supersonic shock wave that excites the sensor. Positioned at a known distance above the spark, the sensor's response is captured via a synchronized digital oscilloscope. Unlike bulky shock tube systems, this compact, repeatable setup allows localized high-bandwidth excitation without mechanical triggers or post-processing.

The sensors are tested in a thermally controlled chamber ranging from 25° to 1000°C. A proportional-integral-derivative (PID)-controlled system establishes static

THE TECHNOLOGY HAS APPLICATIONS IN SPACE EXPLORATION, INDUSTRY, AND DEFENSE

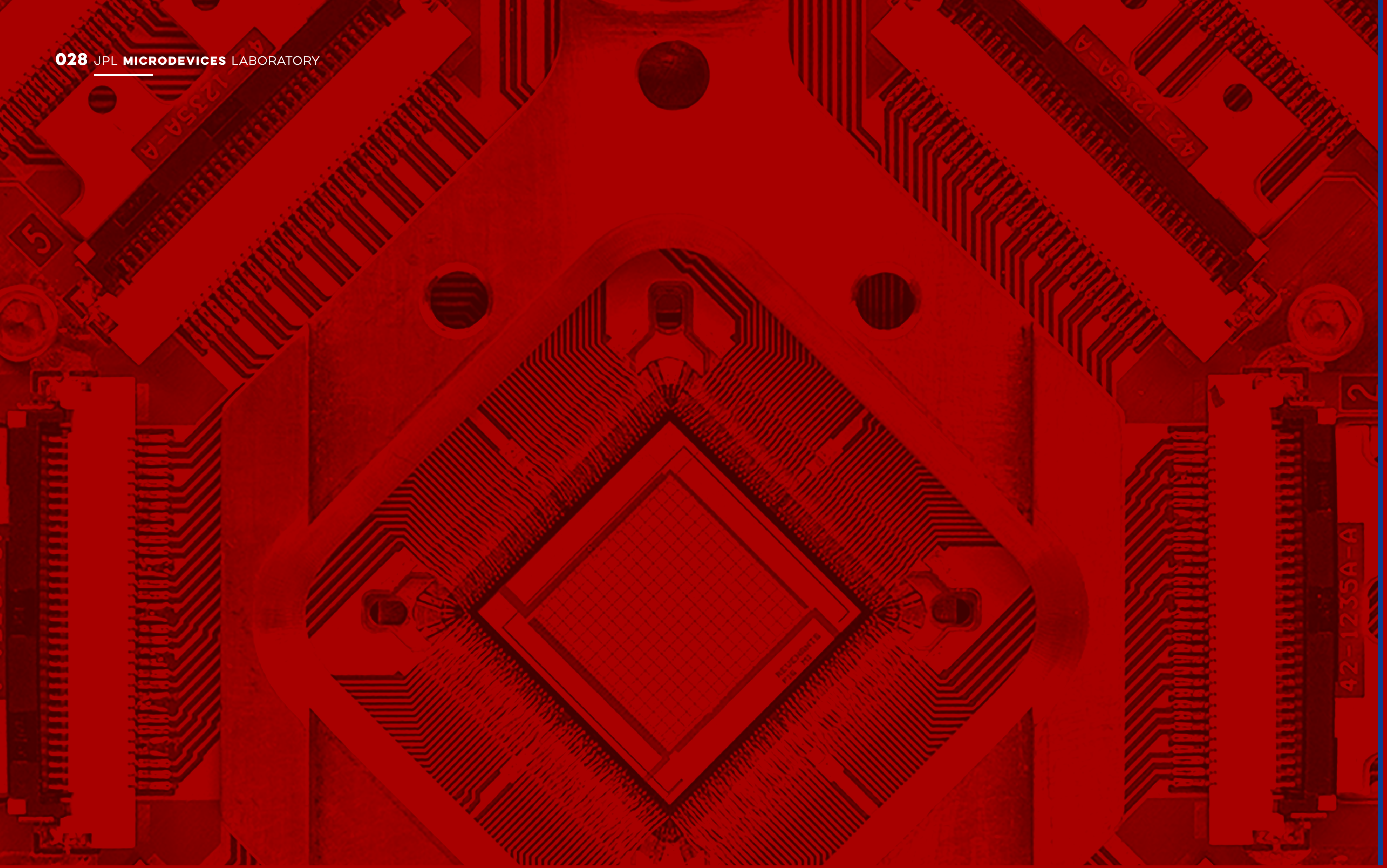
pressures between 1 Pa and 33,000 Pa. The laser-induced transient is superimposed on this baseline, and the sensor's high-resolution response is recorded.

This setup avoids the drawbacks of conventional shock tubes, which require complex equipment and multiple test runs, and produce step-pressure inputs that must be analyzed via Fourier transforms and modeling. Other methods—such as ultrasonic transducers or vibrometry—suffer from limited bandwidth, inaccuracy at high temperatures, or dependence on complex models.

In contrast, the laser-based method enables direct, real-time pressure measurements across a wide range of temperatures and pressures, with minimal complexity and excellent repeatability. Its simplicity makes it ideal for the rapid prototyping and calibration of MEMS sensors.

Strategically, this technology has broad potential beyond its DARPA-funded origins. For planetary exploration, it offers the ability to perform in situ measurements under harsh conditions, such as on Venus or within gas giant atmospheres. In the oil and gas industry, high-temperature sensors can enhance safety and efficiency in drilling and reservoir monitoring. In aerospace, especially hypersonics and propulsion, they enable the real-time monitoring of combustion dynamics.

This work marks a leap in high-temperature dynamic pressure sensing, enabled by advanced MEMS design, robust electronics, and a laser-based test method. It showcases the power of interdisciplinary collaboration and highlights how breakthroughs in measurement science can translate to critical applications across space exploration, industry, and defense.



MDL builds strong partnerships with US industry to accelerate the development and commercialization of advanced micro- and nano-technologies.

Through technology transfer, licensing, and collaborative programs—such as the Technology Affiliates Program and SBIR/Small Business Technology Transfer—MDL supports small-business growth, strengthens domestic manufacturing, and drives real-world product development.

These efforts help maintain US leadership in microelectronics and translate laboratory innovation into practical, commercial applications.

MDL'S COMMERCIAL IMPACT

INDUSTRY

Moving forward the future of QUANTUM

For 20 years, MDL has been instrumental in D-Wave Systems' quantum computing solutions by providing fabrication and R&D services. Fabrication has supported D-Wave's quantum annealing program, and R&D has focused on prototyping, measurement, and analysis.

Since 2004, D-Wave Quantum Inc. (D-Wave) has worked to develop and commercialize quantum computing (QC) by providing a wide range of customers with superior performance that solves high-value problems of commercial or technical interest.

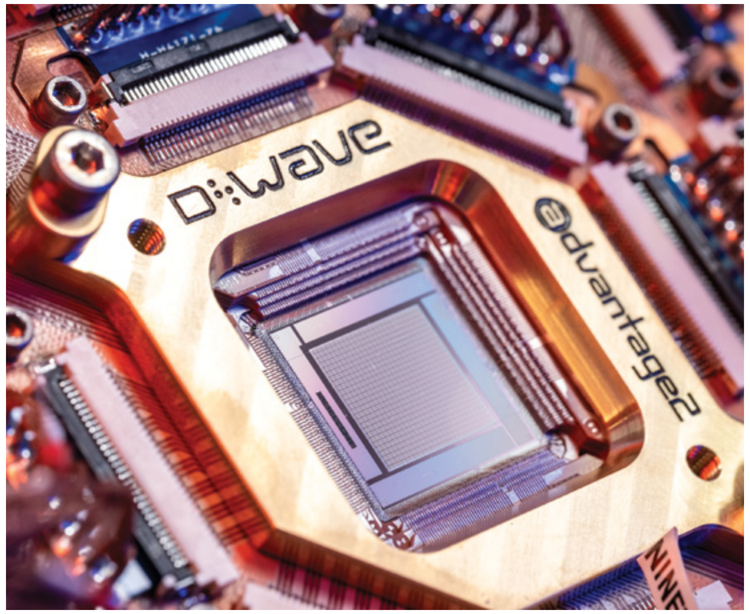
D-Wave has achieved particularly impressive results with quantum annealing (QA), in which challenging combinatorial optimization, machine learning, and scientific problems are mapped onto arrays of superconducting qubits operating at mK temperatures.

In a recent publication in Science, D-Wave showed that their annealing quantum computer achieved a dramatic speedup and improvement of solution accuracy in performing a quantum simulation of frustrated spin-glass systems. This was a demonstration of quantum supremacy on a real-world problem, calculating in minutes what would have taken nearly 1 million years with one of the most powerful conventional supercomputers.

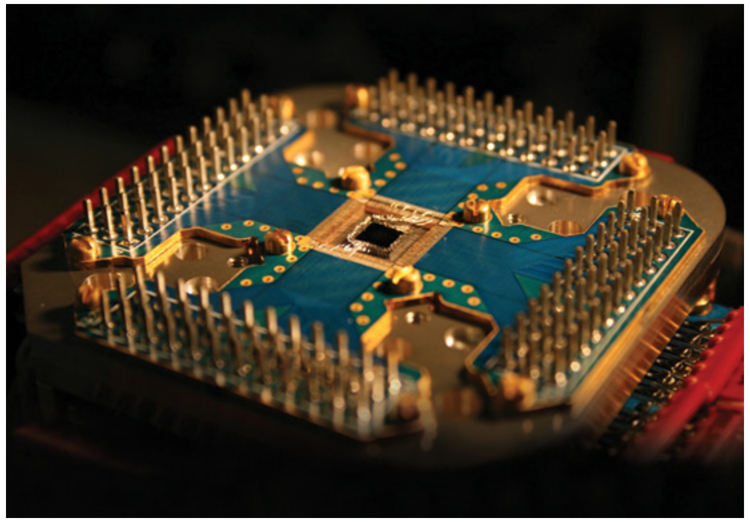
D-Wave's technical approach has depended on the continuous improvement of superconducting qubits, increasing integration scale while reducing device noise and qubit decoherence to enhance the quantum dynamics underlying its computational power. To support this improvement, for over 20 years, D-Wave has worked with the Superconducting Materials and Devices team in support of its QA development, leveraging MDL's decades of experience with ultrasensitive superconducting detectors.

Beginning in 2005, MDL made a fundamental contribution to D-Wave's technology development as the sole supplier of D-Wave's early QA chips.

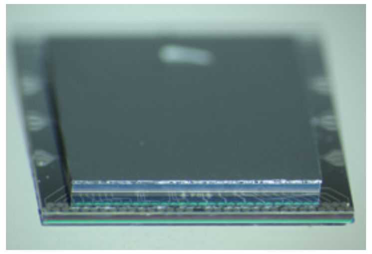
FOR OVER 20 YEARS, MDL HAS SUPPORTED D-WAVE'S FABRICATION AND R&D NEEDS



A D-Wave processor chip made by the D-Wave foundry process that MDL supports.



MDL fabricated chips into D-Wave processors.



A test of flip-chip bonding of superconductor test chips performed at MDL. We will eventually bond qubit chips with classical control chips.

ANNOUCEMENT OF ADVANCEMENT IN THE QUANTUM RACE BY D-WAVE ALLOWED STOCK TO SURGE 28%

By 2008, with help from MDL, D-Wave established a world-leading superconductor fabrication process in a commercial CMOS foundry, the first successful use of a commercial semiconductor foundry to fabricate a product based on a superconducting integrated circuits (ICs).

Today, this collaboration has culminated in arguably the world's most advanced superconducting IC process. D-Wave's very-large-scale integration (VLSI) processor chips are currently manufactured at SkyWater Technology Foundry in Bloomington, Minnesota. MDL has also continued its successful collaboration with D-Wave in an R&D role, supplying essential foundry support with rapid prototyping, measurement, and analysis.

The MDL effort has emphasized forward-looking investigations into problems that represent the greatest challenges to D-Wave's continued success, helping D-Wave to mature and extend its capabilities by solving problems related to decoherence, power reduction, and device physics; prototyping new circuit concepts; and supporting D-Wave's fabrication process.

Most of the worldwide effort to develop quantum computation is based on gate-model quantum computing (GMQC), which is complementary to QA in application but much more difficult to scale to large qubit counts; it is therefore taking much longer to develop to a useful scale.

D-Wave's numerous demonstrations of increasingly powerful QA processors have allowed it to tackle a wide range of difficult and commercially valuable and/or scientific tasks, in some instances outperforming conventional computers and all current GMQC machines by large margins. Although GMQC may never surpass QA in application areas related to optimization, it is generally expected to eventually dominate in some other types of problems, such as in quantum chemistry.

D-Wave is actively working to expand its technology to include GMQC. It is leveraging its unique superconducting IC technology to fabricate high-coherence qubit circuits with integrated control circuitry, enabling a fully scalable approach to GMQC. Success with both QA and GMQC would dramatically widen the range of problems addressable with D-Wave's technology.

MDL is expected to continue in its vital R&D role in this development.

CARBON MAPPER

emissions map

The evolution from the AVIRIS instrument to the Carbon Mapper methane detection system illustrates a significant advancement in remote sensing technology for monitoring greenhouse gas emissions.

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), developed by JPL, was initially designed to study Earth's surface composition. Its successor, AVIRIS-Next Generation (AVIRIS-NG), enhanced these capabilities, enabling high-resolution detection of methane (CH_4) and carbon dioxide (CO_2) emissions from various sources, including oil fields, landfills, and agricultural sites. AVIRIS-NG has been instrumental in identifying and quantifying CH_4 emissions, contributing to targeted mitigation efforts.

Building on the success of airborne instruments, NASA launched EMIT aboard the ISS in July 2022. While EMIT's primary mission was to map mineral dust sources, it demonstrated the capability to detect methane plumes from space, marking a significant step in global greenhouse gas monitoring.

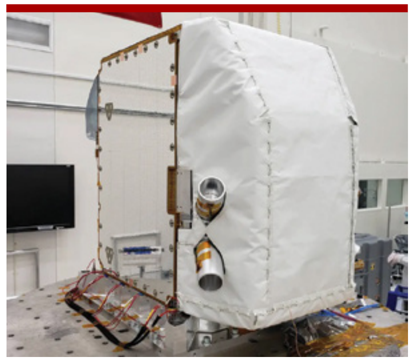
Carbon Mapper, a nonprofit organization, collaborates with partners like NASA JPL and Planet Labs PBC to deploy satellites equipped with advanced imaging spectrometers. These satellites aim to provide high-resolution, facility-scale data on CH_4 and CO_2 emissions, enhancing transparency and enabling targeted mitigation strategies.

MDL contributed to the fabrication of the spectrometer's optical elements which, are essential for detecting and measuring greenhouse gases like CH_4 and CO_2 with high precision. The diffraction gratings, precision slits, and stray light traps are the result of more than a decade of MDL electron-beam diffractive optics fabrication development and refinement, as well as use and testing in previous imaging spectrometer instruments.

Launched on August 16, 2024, the Tanager-1 satellite is the first in a planned constellation designed to detect CH_4 and CO_2 emissions. The satellite carries a state-of-the-art imaging spectrometer developed by JPL, capable of measuring hundreds of wavelengths of light to identify specific gas signatures. This technology allows for the detection of emission plumes with high spatial resolution, enabling the identification of emission sources down to individual facilities.

Since its launch, Tanager-1 has identified several significant greenhouse gas plumes. In Karachi, Pakistan, a CH_4 plume approximately 2.5 miles (4 km) long was detected emanating from a landfill, with an estimated emission rate of over 2,600 pounds (1,200 kg) of CH_4) per hour. Near Kendal, South Africa, a carbon dioxide plume nearly 2 miles (3 km) long was observed from a coal-fired power plant, with a preliminary emission rate of about 1.3 million pounds (600,000 kg) of CO_2 per hour. In Midland, Texas, within the Permian Basin—one of the world's largest oil fields—a methane plume was detected with an estimated emission rate of nearly 900 pounds (400 kg) per hour. Tanager-1 has also observed multiple methane plumes over Syria and Turkmenistan, highlighting the prevalence of "super-emitters" in oil and gas-producing regions.

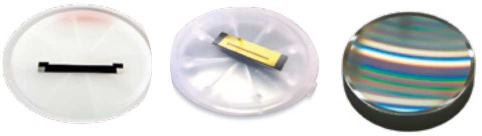
Carbon Mapper has made data from Tanager-1 publicly available through its data portal, providing access to observations of CH_4 and CO_2 super-emitters around the world. This transparency is intended to support climate mitigation efforts by making emissions visible and actionable.



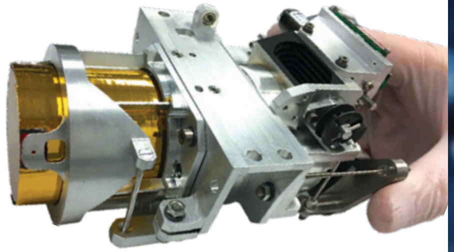
Imaging spectrometer fully integrated.

Carbon Mapper Imaging Spectrometer.

IN A UNIQUE PUBLIC-PRIVATE PARTNERSHIP, CARBON MAPPER WAS DEVELOPED TO IDENTIFY POINT-SOURCE GREENHOUSE GAS EMITTERS AROUND THE WORLD



Light trap   Slit   Grating



Redefining surfaces with ALE & ALP

NanoClear Technologies has adapted MDL's pioneering work in atomic layer etching for use in the industrial-scale ultrafine polishing of over 25 different substrates, including SiC, GaN, SiO_2.

MDL has long used atomic layer etching (ALE) for space applications, such as to thin and smooth superconductors and improve optical waveguide performance and infrared detector dark current. NanoClear Technologies (NCT) recognized that with key enhancements and novel chemical approaches, MDL's pioneering work in atomic layer etching could be extended to the ultrafine polishing of surfaces.

NCT's technology, Atomic Layer Polishing (ALP®), has been adapted to meet the evolving needs of commercial partners in the semiconductor and advanced technology sectors. ALP has been exclusively licensed by Caltech to NCT, which has tailored the technology for industrial-scale use in areas such as AI, quantum computing, and power electronics. ALP uses "tunable" chemical formulations that can be precisely adjusted to smooth and polish over 25 different substrates with complex topologies, including silicon carbide (SiC), gallium nitride (GaN), ruthenium, and silicon dioxide (SiO_2). This flexibility allows manufacturers to achieve sub-nanometer surface finishes tailored to specific materials and device architectures. Unlike traditional chemical mechanical polishing (CMP), ALP employs a non-contact process that eliminates mechanical stress, scratches, and subsurface damage. This approach enhances yield and reliability, particularly for delicate or complex 3D structures that are challenging for conventional methods.

Translating ALP into a commercial setting came with many challenges. ALP was initially designed for small-scale, high-precision applications, such as space optics. Scaling the process for industrial manufacturing required NCT to adapt to smoothing larger substrates with higher throughput without compromising precision. NCT also initially faced capital constraints that made it challenging to quickly commercialize ALP and other nanoparticle coating technologies. They adapted by restructuring their management team, adding new and experienced executives; focused resources on one technology; pivoted the technology towards the semiconductor industry; and leveraged relationships to obtain critically important equipment and laboratory access, which led to raising bridge financing and positioning the company for a Series A financing round.

MDL'S EXPERTISE IN ATOMIC LAYER ETCHING HAS BEEN ADAPTED FOR SURFACE POLISHING

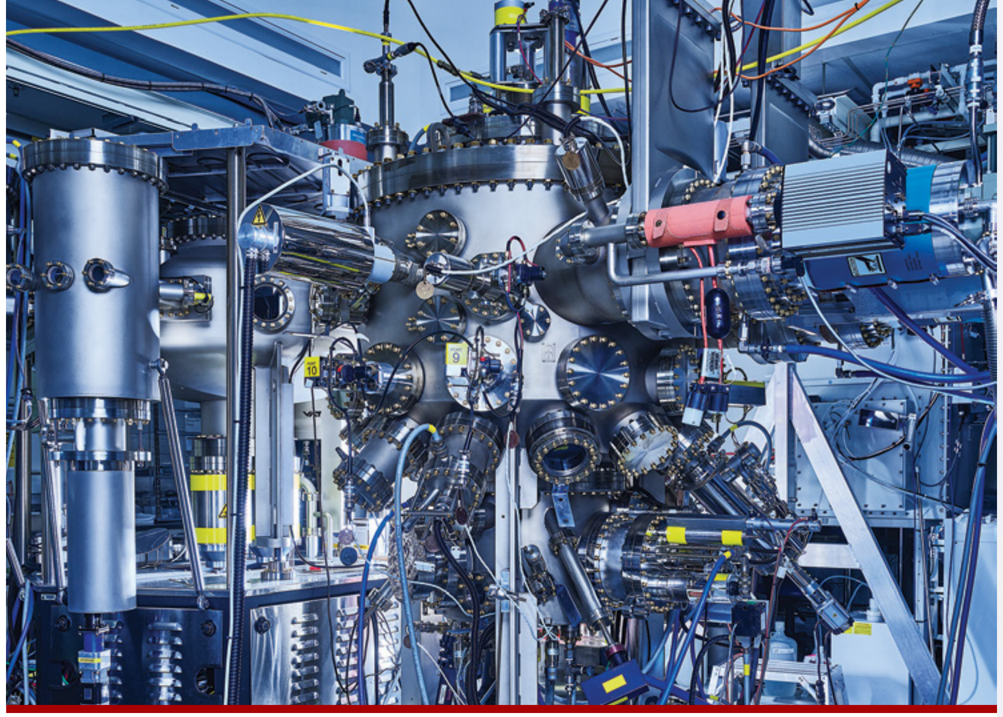
NCT then had to convince stakeholders to adopt ALP by demonstrating not only its technical superiority but also its economic and environmental advantages over traditional methods like CMP. Once their stakeholders were convinced, NCT needed to achieve customer-specific performance standards with diverse materials of various shapes and sizes.

Despite these hurdles, NCT's persistence has paid off: Their adaptation of atomic layer etching has proven extremely valuable to industry, as evidenced by their many customers, including Intel, Soitec, and Sumitomo Chemical. They and others use ALP for precision smoothing at the angstrom level and as a complement to CMP. ALP is primarily being used to smooth hard-to-smooth substrates and 3D surfaces to <0.2 nm root mean squared (RMS). This level of precision is essential for high-performance computing and quantum devices because it minimizes electromagnetic interference and signal distortion, enhancing device performance. For example, in quantum computing, ALP's ultra-smooth surfaces reduce quantum noise and improve qubit coherence times. For AI processors, smoother surfaces enhance thermal conductivity and signal clarity, leading to better performance.

ALP systems are designed for seamless integration into existing manufacturing lines, supporting various stages from in-process measurements to final polishing and wafer refurbishment. This design lowers the cost of adoption for manufacturers. Additionally, ALP's touchless process reduces the need for consumables like slurries and pads, minimizing waste and lowering operational costs. Its eco-friendly nature aligns with industry goals for sustainable manufacturing practices. Together, these qualities support NCT CEO Marshall Smith's vision "to be the global leader in surface innovation, enabling the next breakthroughs in AI, quantum computing, and advanced displays."

UV DELTA-DOPED SENSORS

Delta-doping was invented at MDL to correct a problem with the Hubble Space Telescope. Since then, the technology has been licensed to Alacron, Inc., a company focused on imaging and machine vision. A delta-doped silicon detector developed under this license recently showed unsurpassed stability after intense ultraviolet radiation.

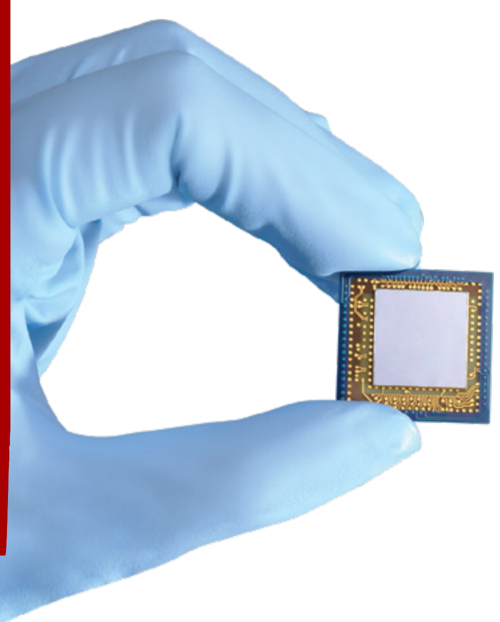


The Molecular Beam Epitaxy (MBE) system enables deposition of nanometer-scale delta-doped silicon with precise tolerances of layer thickness and doping levels.

During pre-flight testing, the charge-coupled devices (CCDs) developed for the Hubble Space Telescope's Wide Field/Planetary Camera (WF/PC) instrument exhibited instabilities at levels as high as 50%, far greater than the stability requirement of 1%. This failure resulted from the "surface problem" in the instrument's silicon image sensors.

Efforts to address this mission-critical problem led researchers at MDL to invent delta-doped silicon detectors. Their work represented a radically new approach to address the surface problem by re-engineering the silicon surface on sub-nanometer-length scales to create the first delta-doped CCDs.

Delta-doping technology enables high sensitivity across a wide range of wavelengths, spanning soft X-rays, ultraviolet (UV), visible, and near infrared. Delta-doped imaging detectors also exhibit unparalleled response stability against surface damage from high-intensity radiation.The high sensitivity and stability of delta-doped image sensors has attracted the interest of multiple commercial entities that are developing sensors for both space and terrestrial applications.



Left: Delta-doped CMOS imaging array

Alacron, Inc. has a worldwide licensing agreement with Caltech to use delta-doping technology for industrial applications, and the delta-doped image sensor technologies invented at MDL are being transferred to industry as an enabling capability for manufacturing the next generation of silicon integrated circuits.

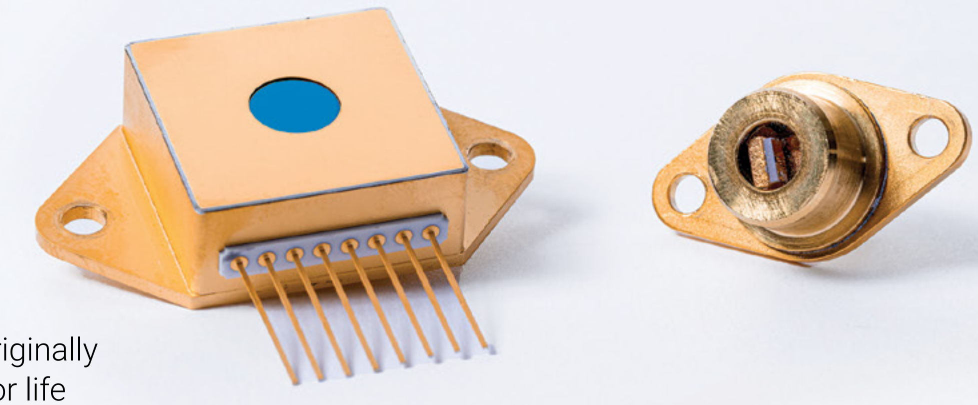
Importantly, delta-doping supports greater tolerance to deep UV damage, which otherwise would cause irreparable damage to detectors. Delta-doped CMOS image sensors (CIS) produced under the collaboration between MDL and Alacron recently surpassed expectations by surviving intense radiation with UV lasers without any measurable degradation in sensitivity or performance. These lifetime tests demonstrated stability against ionizing radiation at doses as high as a petarad (10^{15} rads).

The sensitivity and absolute stability of delta-doped silicon detectors are unsurpassed by any other silicon detector.

MDL-DEVELOPED DELTA-DOPING TECHNOLOGY ENABLES EXCEPTIONAL RESPONSE STABILITY

TLS for methane detection

MDL's tunable laser spectrometer (TLS), originally developed to search for life on Mars, is now licensed by two companies to detect methane leaks in the oil and gas industry.



Above: A low-power dissipation interband cascade (IC) laser fabricated at MDL inside a package designed specially for TLS. This device emits at 3.27 μm and was designed specifically to target absorption lines of methane.

Most methane is generated by bacterial activity, and when Earth-based observations suggested that there might be methane and, by extension, bacterial life, on Mars, JPL scientists created a TLS that could travel on board the Curiosity rover and search for methane from the Martian surface. That version of the TLS landed on Mars in 2012 and continues to send back data, but the technology has also found a critical use on Earth: Supporting methane leak detection in oil and natural gas production.

Given its commercial potential, the TLS used on Earth was first developed in 2013. It is a miniaturized version of the original, small enough to ride on a drone or be packaged into a handheld device. Shrinking the instrument required sacrificing some sensitivity—it is approximately 100 times less sensitive than the TLS on Mars—but this lower sensitivity is still more than adequate for its industrial applications; gas leaks are usually detected at 50–100 parts per billion, and the TLS is capable of detecting as little as 10 parts per billion. Additionally, the instrument is still quite powerful, running as many as 10 analyses per second.

In 2017, two key licensing agreements for this miniaturized TLS technology were reached: One agreement was used to found Pasadena, California-based SeekOps, and the other was used to license the technology to the Union City, California-based RKI Instruments, Inc.

SeekOps provides methane detection services to the oil and natural gas industry, using their sensors on site to pinpoint the location of leaks. The technology is far superior to its predecessors: With their JPL-based technology, SeekOps can conduct a full well-pad inspection in approximately 15 minutes, making it 1,000 times more sensitive than older technologies. Their analyses are more accurate and comprehensive than the competition and can be conducted in approximately one-third of the time.

Similarly, RKI Instruments produces compact, lightweight sensors that can be flown on drones or used as handheld devices to quickly locate leaks. Their drone-based devices can be used to complete site surveys in minutes or hours, compared to the days or weeks needed using traditional methods.

Thus, JPL's TLS technology has promoted value in the oil and natural gas industry in three ways: It supports short-term safety by detecting active leaks of combustible products, it supports long-term safety by identifying areas that could eventually become leaks, and it supports profitability by helping minimize product loss. In addition, since methane is a greenhouse gas, detection and elimination of methane leaks will reduce the carbon footprint and are environmentally sound.

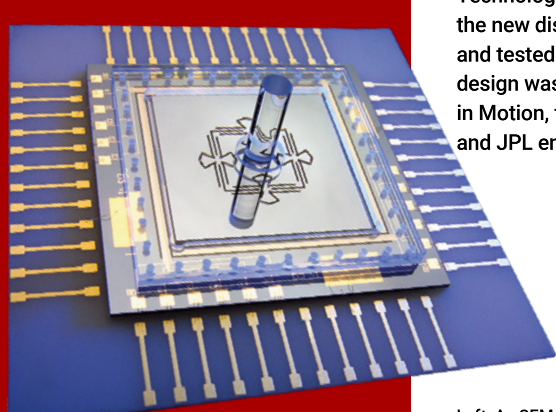
MDL FABRICATED A LOW DISSIPATION IC LASER AND PLACED IT IN A SPECIALLY DESIGNED TLS PACKAGE

Methane leak detection with SeekOps drone-mounted sensor.

MEMS
Inertial sensor technology

Advances in nano- and micro-technologies drive development of electronics and sensors in our everyday lives and in Earth and planetary exploration.

THE MDL-DEVELOPED DISC RESONATOR GYROSCOPE IS THE WORLD'S HIGHEST-PERFORMANCE MEMS GYROSCOPE



Left: An SEM photo of a fabricated MDL MEMS gyroscope.

Before 1994, spacecraft gyroscopes relied on spinning masses with moving parts prone to wear, which limited their lifespan. In 1994, Delco Systems adapted its Hemispherical Resonator Gyroscope for space, demonstrating a simplified version with no moving parts that could operate continuously. It was later adopted in Boeing's TDRS-H, -I, and -J satellites, launched in 2000.

Around the same time, micro-electro-mechanical systems (MEMS) were adapted in automotive safety. MEMS enabled hundreds of micro-mechanical resonators to be fabricated on a single silicon wafer using photolithography, paving the way for smaller, cheaper, and more robust spacecraft sensors.

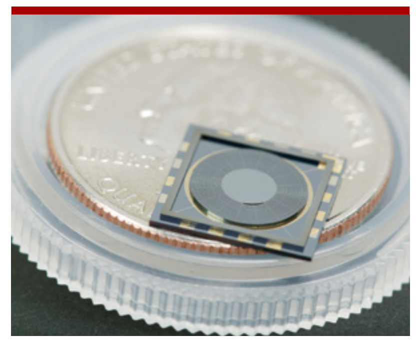
MDL joined a DARPA-funded consortium with Boeing HRL and UCLA to develop MEMS for space applications. In 1997–98, the MDL team built JPL's first all-silicon MEMS vibratory post gyroscope, featuring a central silicon post with four surrounding petals. Two petals drove the post like a pendulum, while angular motion caused precession detected by the other two. This closed-loop sensor achieved ~0.1°/hr bias stability.

In 2002, the MDL team advanced their MEMS gyroscope design into a larger mesoscale version, achieving ~0.01°/hr bias stability. However, its out-of-plane central post necessitated complex 3D packaging and vacuum sealing. To address these challenges, in 2003 MDL developed a new version—a planar silicon disc resonator gyroscope, which maintained a comparable performance while simplifying packaging requirements.

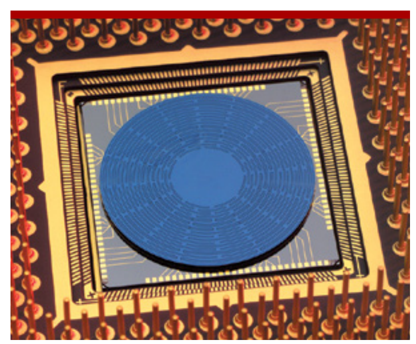
Technologists at MDL further modeled the new disc design, and JPL fabricated and tested it with Boeing funding. The design was licensed to a startup, Sensors in Motion, founded by former Boeing and JPL engineers.

They produced and sold MEMS gyroscopes with bias stability as low as 0.01°/hr. Sensors in Motion was later acquired by Garmin. Honeywell, Inc. independently tested and used MDL-developed MEMS gyros in various aerospace and autonomous systems.

MEMS gyroscopes are essential for GPS denied navigation. For example, a Mars rover turning just 3° and traveling 1 km without external guidance must maintain accurate orientation. Even a 1° error could distrupt communication or misalign solar panels. MEMS gyros enable precise angular motion sensing to reduce such mission failures.

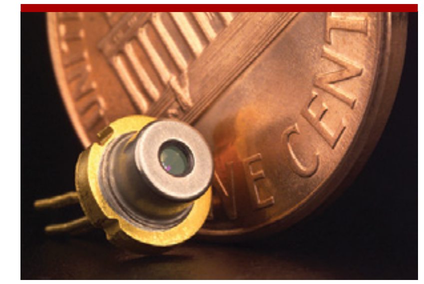


MDL's miniature disc resonator gyroscope.



Disc resonator gyro.

Sensors in Motion first MEMS navigation-grade inertial system.



Miniaturized tunable diode laser packaging for sensing and measuring atmospheric water vapor.

UPS now flies the technology on its aircraft to improve weather forecast accuracy.

The aerodynamic air sampler mounts to the aircraft exterior and removes ice, particles, and rain for more accurate measurements.

Endress+Hauser's gas analyzer uses patented TDLAS technology for precise H_2O measurement in gas applications. Credit: Endress+Hauser.

SPECTRASENSORS WAS ACQUIRED IN 2012, AND THE TECHNOLOGY HAS SINCE FOUND SUBSTANTIAL USE IN THE AVIATION, NATURAL GAS, AND HYDROCARBON INDUSTRIES

Tunable diode lasers in space and on Earth

MDL-developed tunable diode laser technology led to the formation of the spinoff company SpectraSensors, which was acquired in 2012, and the technology has since found substantial use in the aviation, natural gas, and hydro-carbon industries.

Tunable diode lasers were originally developed at MDL in the 1980s. Much like a radio can be tuned to different frequencies, these semiconductor-based lasers can be tuned to different wavelengths to focus on molecules of interest, including small trace gases. They were designed to emit near-infrared light at wavelengths absorbed by the gases being detected. The light energy being absorbed by the target gas is related to the molecules present, which are usually measured in parts per million or parts per billion. Multiple measurements are made every second, making the system quick to respond to variations in the target gas.

Tunable diode lasers were initially used on Earth to support studies of the atmosphere, and subsequent advances in miniaturization meant that these devices traveled to Mars as early as 1999 as part of the Mars Polar Lander mission. NASA has since used this tunable diode laser-based gas sensor on aircraft and on balloons to successfully study weather and climate, global warming, emissions from aircraft, and numerous other areas where chemical gas analysis is needed.

Key innovators of this technology, Randy May and Carl Kukkonen, recognized that tunable diode lasers could have industrial applications on Earth, and in 1999, they founded SpectraSensors to commercialize the technology. One of SpectraSensors' early products was the Water Vapor Sensing System-II (WVSS-II), which was certified by the Federal Aviation Administration for commercial flights in 2004.

It combined the tunable diode laser developed at MDL with an air sampling device licensed from the University Corporation for Atmospheric Research. The instrument was designed to be flown on a plane, where it would take measurements every 2 seconds; a fleet of 25 aircraft containing the WVSS-II would be able to collect more data on water vapor than all the weather balloons and satellites in use at the time. This unprecedented amount of data would help with aviation safety since water vapor affects clouds, wind shear, and turbulence. By 2006, United Parcel Service was flying the WVSS-II on its aircraft to help improve the reliability of weather forecasts.

In 2012, SpectraSensors was acquired by Endress+Hauser, and in 2021, a new line of sensors for the hydrocarbon industry was released. These sensors provide fast, robust, and accurate measurements of molecules such as water, carbon dioxide, hydrogen sulfide, ammonia, and oxygen—all critical to safety and productivity.

Consequently, they are a preferred solution in the hydrocarbon industry: More than 10,000 such analyzers have been installed worldwide. The tunable diode lasers developed at MDL decades ago have thus found new commercial applications supporting aviation safety and natural gas production.

THE AVIATION AND HYDROCARBON INDUSTRIES HAVE BENEFITED SUBSTANTIALLY

MDL is constantly advancing the future of NASA missions with cutting-edge micro- and nano-scale devices. With a focus on innovation, risk-taking, and bold ideas, MDL consistently delivers high-impact solutions that push the boundaries of science and engineering.

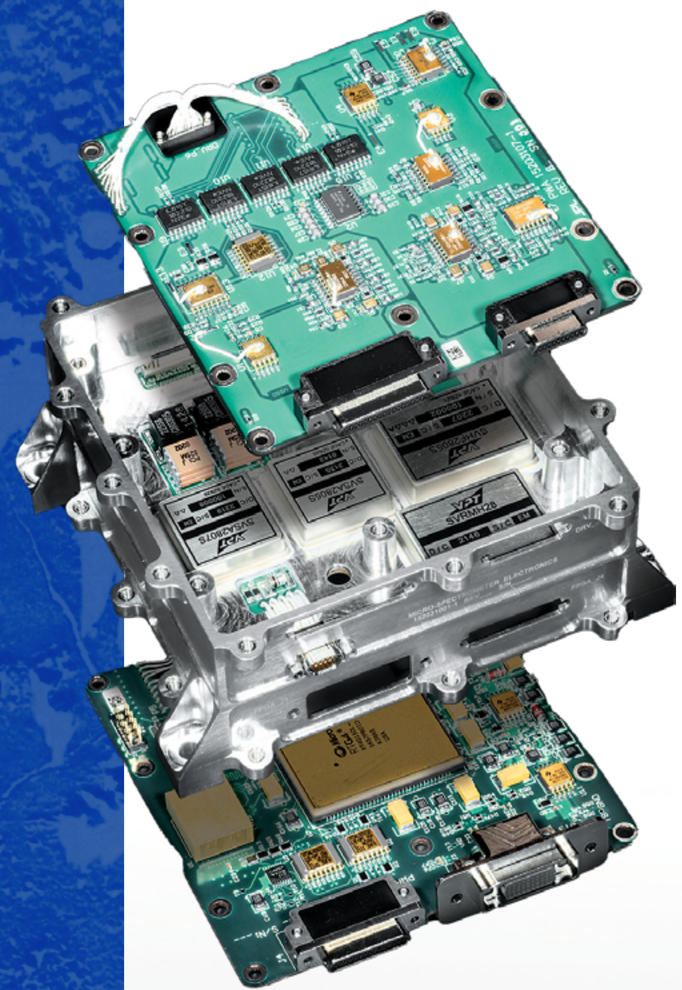
Its multidisciplinary team is shaping the next generation of instruments for space exploration, Earth science, and national applications—from planetary sensing to medical diagnostics. These efforts support NASA's long-term goals across deep space, lunar, and Earth missions.

MDL LOOKS BEYOND TOMORROW

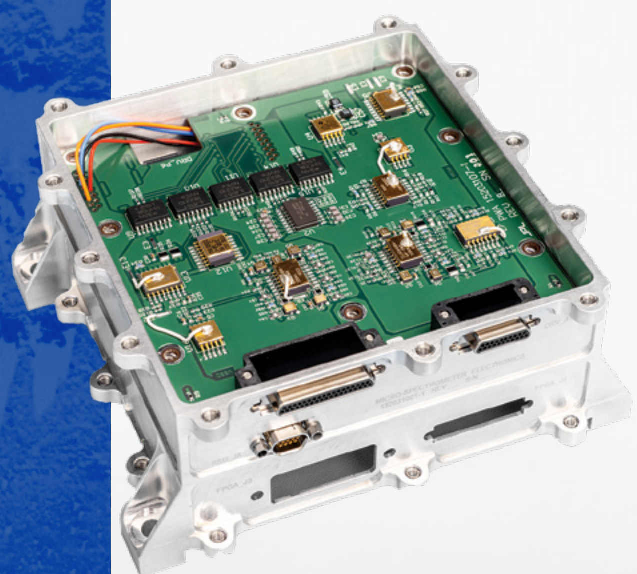
BOLD IDEAS

Hand-held spectrometry with the VMDIS

MINIATURIZED SPECTROMETER TECHNOLOGY WILL ENHANCE MARS HELICOPTER CAPABILITIES



VMDIS circuit boards combined into one compact assembly.



Once assembled, the micro-spectrometer electronics occupy a compact volume with low mass.

"TRICORDER" TO IDENTIFY RESOURCES IN SITU

With a total mass of less than 3 kg, the Visible Mid-wave Dyson Imaging Spectrometer (VMDIS) may one day be used on the Moon or other planets.

It may also be deployed as a handheld device for astronauts, who could use it like a Tricorder on crewed missions to identify resources in situ as humans expand their exploration of the solar system.

Prototype of the VMDIS Helicopter.

The success of the Ingenuity Mars Helicopter demonstrated that aircraft can function in the Martian atmosphere, opening the door to more extensive airborne exploration of Mars in the future.

To that end, JPL's Imaging Spectroscopy team was challenged to create an instrument that could survey Valles Marineris, the largest canyon in the Solar System and home to its oldest observable minerals. It would need to be light enough to fly aboard a helicopter in Mars' thin atmosphere, which limits the instrument's total mass to less than 3 kg.

However, measuring spectra in shortwave infrared wavelengths requires detector cryocooling, as well as electronics capable of recording the wealth of data captured. These subsystems leave less than 1 kg for the optics.

The resulting instrument, the Visible Mid-wave Dyson Imaging Spectrometer or VMDIS, has a low-mass optical design thanks to a slit and grating from MDL. The slit is 18 μm wide—as narrow as the pixels in the detector—and the grating is imprinted on a concave surface using MDL's electron-beam lithography.

Since the grating allows the spectra to be separated to a line of detectors, only one other element, a calcium fluoride lens, is needed to create a Dyson spectrometer covering the visible through midwave infrared wavelengths (600–3600 nm).

Light is imaged onto the slit using a two-mirror reflective telescope. The high degree of spectral and spatial uniformity achieved with the MDL-fabricated components requires few computational corrections to the data and allows real-time data interpretation.

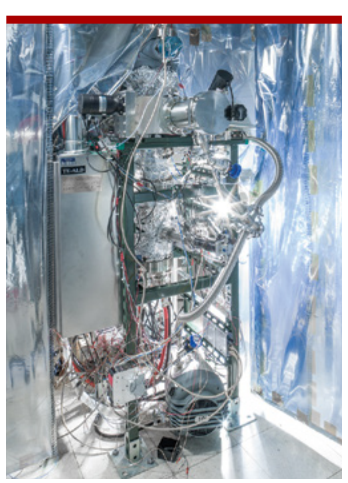
As a pushbroom instrument, VMDIS records 500 spectra simultaneously in three dimensions across a swath of 60°. When it is mounted on a helicopter, an entire area can be mapped spectroscopically as the helicopter flies forward. A prototype of the instrument combining the optics, detector, electronics, and cryocooler has been built to demonstrate its capabilities.

The low mass of the instrument also lends itself to astronaut-deployed and even hand-held spectrometers. These tools would enable astronauts to identify minerals and resources, like water and building materials, in situ for mission use.

The technology is adaptable to both lunar and Martian environments, essentially giving astronauts a "Tricorder" they can use as humanity expands its exploration of the solar system.

Probing the unseen ultraviolet universe with UVEX

The Ultraviolet Explorer (UVEX), planned for launch in 2030, will investigate the entire sky in the near- and far-ultraviolet range. Thanks to MDL's expertise in delta-doping and coating techniques, UVEX is 50 times more sensitive than its predecessor and thus will be able to address key questions raised in the 2020 Decadal Survey on Astronomy and Astrophysics.



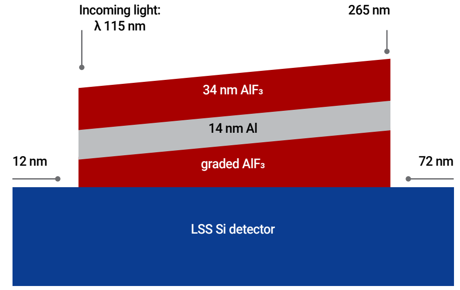
TEALD and clean tent.

UVEX BENEFITS FROM MDL'S EXPERTISE IN DELTA-DOPING AND COATING TECHNIQUES

UVEX is targeted to be NASA's next Astrophysics Medium-Class Explorer mission. It will undertake a synoptic survey of the entire sky in the near-UV and far-UV, probing the dynamic universe with a sensitivity more than 50 times better than its predecessor, the Galaxy Evolution Explorer (GALEX). UVEX will have a wide-field, two-band UV imager and a long, multi-width slit spectrometer, giving it powerful broadband spectroscopic capabilities. Consequently, it will be able to address fundamental questions from the 2020 Decadal Survey on Astronomy and Astrophysics and study the evolution of low-metallicity, low-mass galaxies. UVEX time-domain surveys will probe the aftermaths of gravitational wave-discovered compact object mergers, discover fast UV transients, and diagnose the early stages of explosive phenomena.

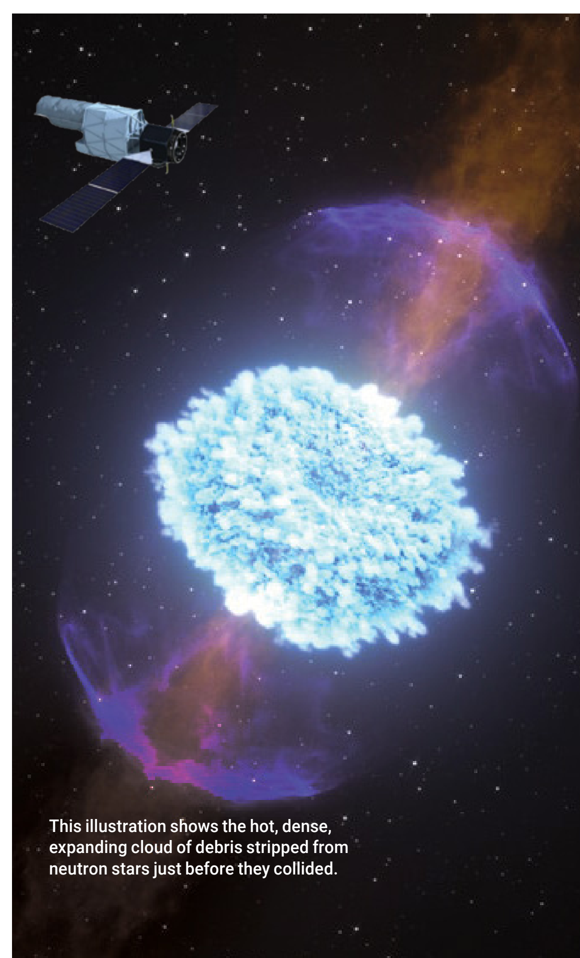
UVEX baselines MDL's delta-doped UV detectors for both its wide-field imaging system and multi-width slit spectrometer. The wide-field imager will include a 3 × 3 mosaic of large-format (4k × 4k) CMOS CIS. The CIS detectors will be optimized for UVEX with delta-doping, a custom antireflection coating, and UV bandpass filters developed at MDL using techniques such as molecular beam epitaxy and atomic layer deposition. Similarly, the spectrometer's detector will be delta-doped for UV optimization. Bandpass optimization will be achieved with state-of-the-art coating techniques developed at MDL that allow for spatially varying the response of silicon UV detectors.

Together with the MDL Support group, the UVEX Detector team has taken steps to transition from technology development to flight implementation. This effort has included upgrading the detector characterization lab, as well as MDL's custom-built thermal evaporation/atomic layer deposition (TEALD) system. The characterization lab's vacuum UV monochromator is a workhorse tool for the UV Detector team and was previously used to test devices for missions such as Cassini, the Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall)-2, and the Star-Planet Activity Research CubeSat (SPARCS). In preparation for UVEX, the monochromator system has been retrofitted with a custom test dewar/cryostat, clean tent, and state-of-the art electronics for improved system cleanliness and stability. UVEX has a target launch date of 2030, and the project is led by Caltech.



Geometry showing the graded filter to be deposited on the LSS surface.

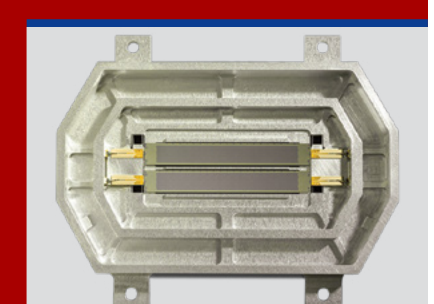
Monochromator for improved cleanliness and stability.



This illustration shows the hot, dense, expanding cloud of debris stripped from neutron stars just before they collided.

Microwave kinetic inductance detectors for PRIMA

MKIDs are key to the extraordinary sensitivity of the Probe far-Infrared Mission for Astrophysics (PRIMA) telescope. MDL and its collaborators continue to push the boundaries of MKID performance for future missions in far-infrared astrophysics.



MKID arrays packaged for testing in PRIMA spectrometer brassboard.

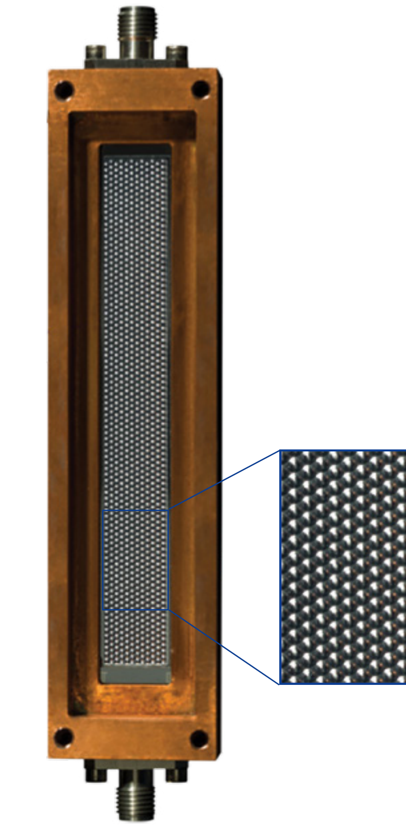
Optical microscope image of PRIMA MKID array.

MKIDs are ultra-sensitive detectors for far-infrared astronomy. They can be elegantly multiplexed to form kilopixel-scale FPAs that are read out through a single microwave readout line. First invented 25 years ago at MDL, the MKID has been scaled up and demonstrated on-sky in various ground-based and suborbital observatories for submillimeter astrophysics. After years of development, MKID technology is now at the heart of PRIMA, a prospective far-infrared space telescope currently in a Phase A concept study.

PRIMA, which will cover a range of wavelengths beyond that of the James Webb Space Telescope (JWST), will have a 1.8 m cryogenic space telescope and an imager and spectrometer covering wavelengths from 24 to 261 μm. It fills an important gap in space-based astronomy between the Mid-Infrared Instrument on JWST and ground-based radio telescopes such as the Atacama Large Millimeter Array. PRIMA will represent an eight-order-of-magnitude improvement in sensitivity over now-discontinued submillimeter assets such as the Stratospheric Observatory For Infrared Astronomy (SOFIA); this improvement is the equivalent of conducting optical astronomy with nighttime backgrounds instead of daylight.

This spectroscopy requires large arrays of sensors with almost unimaginable sensitivity. In response to these requirements, MDL has recently demonstrated world-leading MKID arrays with a noise-equivalent power of 4×10^{-20} W/√Hz at 10 Hz, which means that the sensors can resolve a faint optical flux of only 40 zeptowatts in a tenth of a second and measure it across 1,000 sensors simultaneously.

MDL WILL ENABLE THIS PROJECT BY FABRICATING THE LARGE-FORMAT SUPERCONDUCTING MKIDS



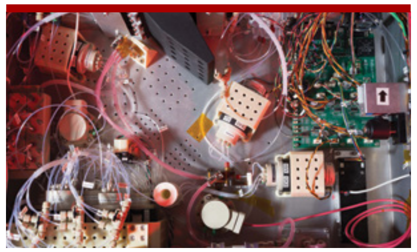
MKID array hybridized with GSFC silicon microlenses.

This sensitivity corresponds to single-photon counting at a wavelength of 25 μm, which represents a new milestone for the superconducting detector community. In the past year, MDL has developed novel nanofabrication processes that enable ultra-high-quality superconducting microwave resonators coupled to mesh absorbers with a linewidth of only 100 nm. These arrays are currently being flight qualified and scaled for direct infusion into PRIMA.

JPL is collaborating on this technology development with Goddard Space Flight Center (GSFC), which is hybridizing the detectors with lithographically fabricated silicon microlens arrays and leading the development of the readout application-specific integrated circuits (ASICs). Together, JPL and GSFC are using MDL technology to lead the way in a new era of far-infrared astrophysics.

A primary objective of future planetary missions is the search for signs of life beyond Earth. Biosignatures can take the form of complex organic molecules or distributions of smaller molecules, such as amino acids. Thus, future missions looking for evidence of life will need chemical analyzers that can identify trace levels of these chemical fingerprints. Over the last 20 years, MDL has been developing hardware and protocols to meet the needs of such future life-detection missions. For example, MDL is developing the Organic Capillary Electrophoresis Analysis System (OCEANS), the most capable hardware to perform in situ liquid-based analyses as well as analytical strategies to detect the widest possible range of chemicals, which will help astronauts prepare for the unexpected during future exploratory missions.

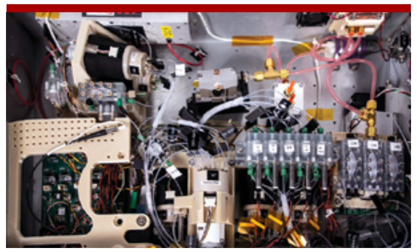
Chemical analysis is performed via capillary electrophoresis coupled to multiple detection systems and an array of ion-selective electrodes. The use of liquid-based electrophoretic separation in the search for life is particularly powerful, enabling the analysis of a wide range of soluble organic and inorganic compounds. The identification and quantification of each compound in a sample can yield biosignatures that could indicate the presence of life. To cast the widest possible net within the chemical space, three complementary detection systems are used: Laser-induced fluorescence (LIF) to enable the sensitive analysis of amino acids, which the astrobiology community considers one the strongest biosignatures; contactless conductivity detection (C4D) to detect inorganic ions and metabolic products; and mass spectrometry (MS) to detect fatty acids and a broad range of organic compounds, as well as to identify unknown species in the sample.



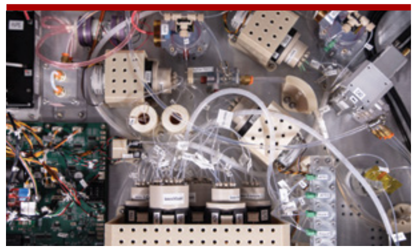
Capillary Electrophoresis (CE) Electrospray Ionization (ESI) Mass Spectrometry (MS) enables a broad survey of biomolecules at high sensitivity.

In 2022, the end-to-end automated operation of the OCEANS hardware was demonstrated at Mono Lake, California. Since then, the technology has consistently progressed for future flight implementation. OCEANS uses multiple chemicals, including water, organic solvents, chiral selectors, buffers, and fluorescent dyes, that must survive a range of conditions over the multi-year duration of a mission. Hence, it is essential to validate that they will function properly after long-term storage in these environments.

In 2024, accelerated aging was performed to simulate storage conditions at 55°C for 15 years to match possible timelines for future missions to ocean worlds. These conditions were selected to represent the most extreme case: a mission to Enceladus with the spacecraft payload being held at its highest possible temperature continuously for the duration of the mission. All reagents could still be used to perform successful analyses after exposure to these thermal conditions. These results, combined with a previous demonstration of reagent tolerance to high levels of radiation, completes reagent qualification for use on future spaceflight missions. This is a critical step in advancing this technology for future missions to ocean worlds like Europa and Enceladus.



CE-LIF is the most sensitive technique available for analysis of amino acids and their chirality.

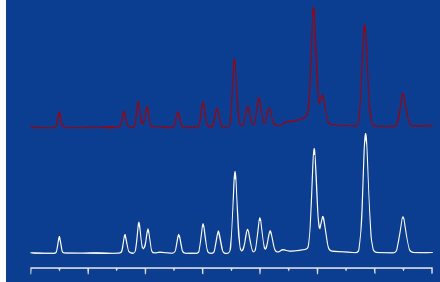


CE-C4D enables a broad survey of metabolically important organic molecules.

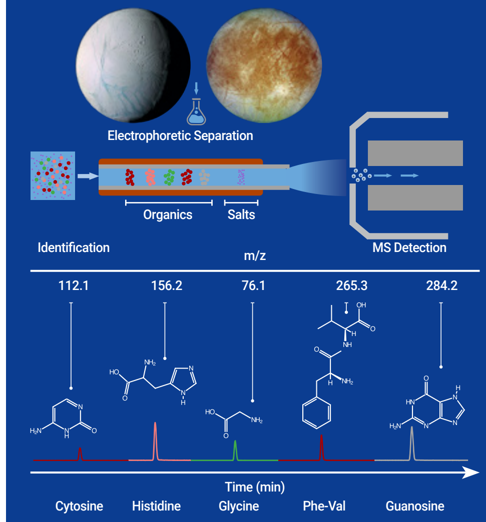
Looking for life beyond Earth

OCEANS is designed to detect key molecular signatures of life, such as amino acids and fatty acids, on Earth and on ocean worlds beyond it.

ESSENTIAL REAGENTS ARE NOW QUALIFIED FOR LONG-TERM MISSIONS



Example analysis of amino acids with both control and aged florescent dye. There are no clear differences in the electropherograms of the amino acid mixtures labeled using the aged dye and the control.



24/7 monitoring of space weather with THz instrument

Since 1990, MDL has prioritized submillimeter wave advanced technologies to support research in the terahertz range. The resulting instruments have helped and will help answer fundamental questions, including how stars form and how the wind behaves high above Earth's surface.

Although at least 98% of the detectable radiation energy in the universe falls in the terahertz range, in the late 20th century, most people had never heard of terahertz radiation. However, because of the demand to explore this vast, unknown part of the electromagnetic spectrum, MDL began work on submillimeter wave advanced technologies in early 1990. The goal of this effort was to drive breakthroughs in the status quo of terahertz research and support continuous improvement that would enable new science missions using terahertz heterodyne instruments. Since then, MDL has successfully delivered several critical scientific instruments. For example, the Microwave Limb Sounder (MLS) measures hydroxyl radicals, which play a critical role in the ozone destruction cycle; the Microwave Instrument for the Rosetta Orbiter (MIRO) has been used to map the distribution of water in the plume of Comet 67P/C-G as the comet approaches the Sun; and the Heterodyne Instrument for the Far Infrared (HIFI) on the Herschel spacecraft measured the dynamics of star formation.

An example of a cutting-edge terahertz heterodyne instrument is TerraWinds, the world's first all-solid-state 2.06 THz receiver that works at room temperature and will enable 3-D wind velocity measurements. TerraWinds will serve to better understand the 100–400 km altitude above Earth, a fascinating but very poorly understood range where the atmosphere meets space. This part of the atmosphere, consisting of the mesosphere and the lower thermosphere–ionosphere (LTI), is very difficult to measure directly. The LTI is where the thermosphere's neutral gas interacts with the coexisting plasma population of the ionosphere, influenced by forcing from above and below.

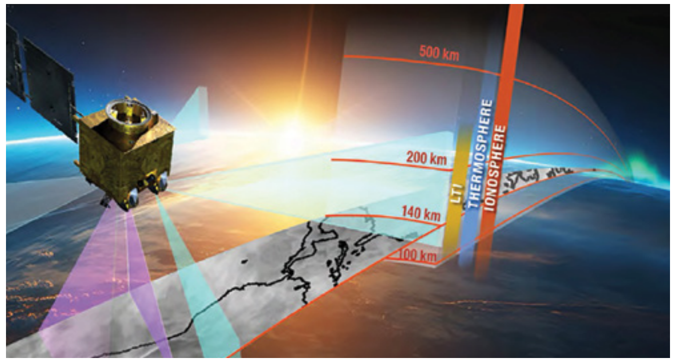
It is home to many important physical processes, such as atmospheric wave coupling and Joule heating. The processes that contribute to the transfer of energy/momentum in the LTI have not been measured with any spatial or temporal fidelity, leading to a critical knowledge gap. Among the least understood phenomena in this range are wind velocities, which are highly dependent on the Sun's energy coupling. To date, only sounding rockets have provided some measurements, but they are instantaneous and only provide a snapshot at a time. Knowledge of these wind velocities is important to model properties such as drag and orientation for assets operating in this range.

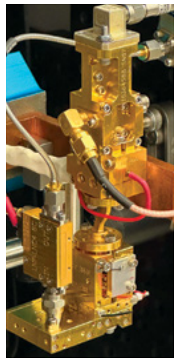
Devices designed and fabricated at MDL make up both the local oscillator and the mixer for TerraWinds. The mixer is of considerable importance: It is the only device of its kind in the world. The selected design concept includes a bias-able anti-parallel pair topology. This topology provides better balance between diodes and is more tolerant of manufacturing deviations and misalignments of the mixer waveguide blocks. This chip was designed and fabricated at MDL, and the gallium arsenide membrane is less than 5 μm thick. The sub-micron anodes were created using MDL's advanced e-beam capability. The receiver has been tested at room temperature and has a double side band sensitivity of better than 7000 K, a world record. The successful implementation of this concept will close fundamental gaps in our understanding of processes that link Earth's atmosphere and space and will advance our knowledge of the magnetosphere-ionosphere-thermosphere's system-level behaviors.

Right: A limb sounding terahertz instrument can provide the first ever global measurement of winds in the 100–250 km altitude range.

Left: A compact all-solid-state receiver at 2.06 THz has been assembled and demonstrated. The receiver uses devices, both multipliers as well as the mixer, fabricated at MDL.

MDL'S SUBMILLIMETER WAVE ADVANCED TECHNOLOGIES RESEARCH HAS ENABLED SCIENCE MISSIONS FOR DECADES





UV spectrometer for future LUNAR exploration

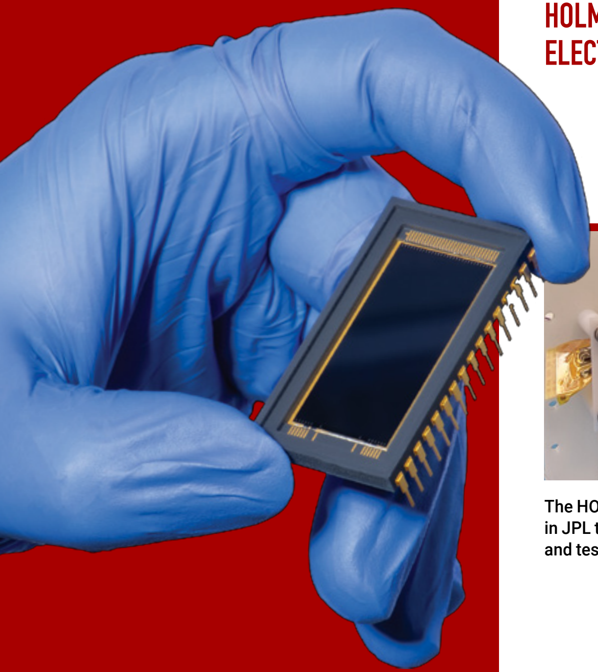
The Heterodyne OH Lunar Miniaturized Spectrometer (HOLMS) would measure the release of hydroxide and water from the surface of the Moon, expanding our understanding of lunar volatile transport.

Two MDL teams—the Advanced Detector and Nanomaterials and the Flight Imaging Systems teams—are working closely with scientists at JPL to develop a spectrometer to study the daytime concentrations of hydroxide (OH) on the lunar surface. HOLMS is designed to survive a mission to the lunar daytime surface and has a science objective to determine the relative contribution of thermal desorption/sputtering and micro-meteoroid impact on the release of lunar exospheric OH and H_2O.

HOLMS would support a key NASA goal of understanding lunar volatile transport by observing the UV emission spectra of OH in the 311–317 nm wavelength range from the Moon's surface.

JPL has developed a very compact spatial heterodyne spectrometer (SHS) that would be paired with MDL's high-efficiency UV detector technology. HOLMS baselines a delta-doped electron multiplying charge coupled device (EMCCD), an enabling technology for the instrument.

The delta-doping process for silicon detectors was first developed at MDL in the early 1990s in response to instability issues encountered during the system-level testing of Hubble's WF/PC. The process uses low-temperature MBE to deposit an extremely thin (few nanometers), highly doped layer of silicon. MBE allows for the precise control of the deposition process such that the dopant atoms are confined to atomically thin sheets within an un-doped silicon host material.



The delta-doped EMCCD is an enabling technology for HOLMS.

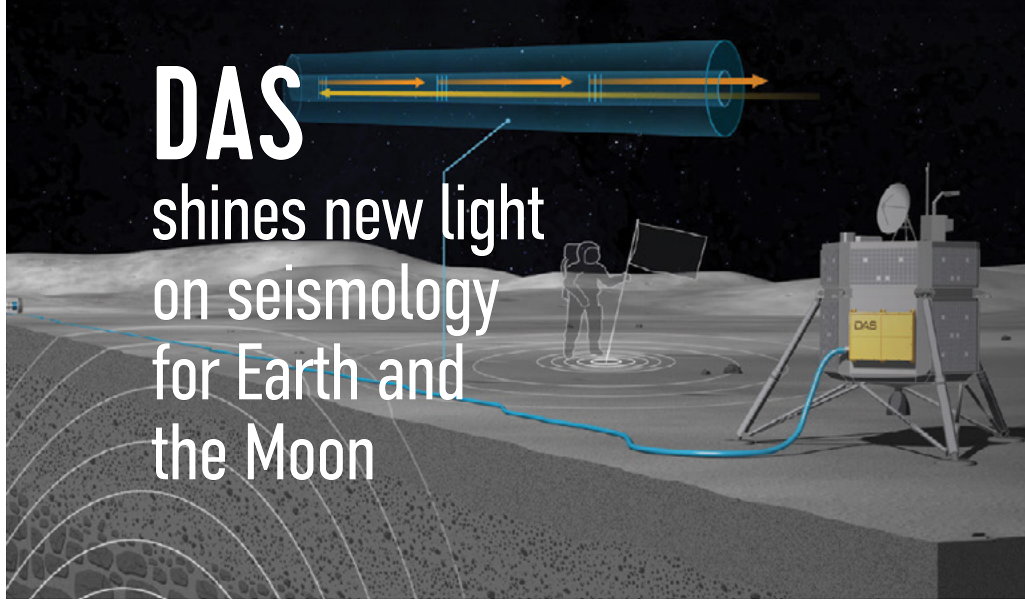
HOLMS BASELINES A DELTA-DOPED ELECTRON MULTIPLYING CCD

FROM THE LUNAR SURFACE, HOLMS WOULD STUDY LUNAR EXOSPHERIC HYDROXIDE AND WATER

The resulting devices exhibit reflection-limited response, with sensitivity spanning X-ray, UV, visible, and near-infrared wavelengths. When delta doping is applied to EMCCD detector technology, the resulting device has high quantum efficiency and stability, as well as extremely low noise performance, allowing for single-photon sensitivity. These highly capable devices are then optimized for targeted applications with custom antireflection coatings or UV bandpass filters. For the HOLMS 311–317 nm bandpass, the baselined device includes a single-layer hafnium oxide (HfO_2) AR coating deposited via atomic layer deposition, which will result in >60% efficiency throughout the entire wavelength range.

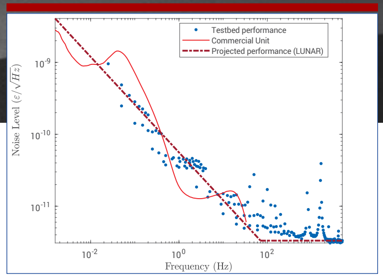
In fall 2024, the HOLMS team successfully completed an extensive test campaign to advance the TRL of the instrument through the verification of its optical performance, as well as its optomechanical assembly. The campaign included vibration testing and thermal cycling under vacuum (TVAC) in a relevant environment. This work, done in collaboration with the Space Dynamics Laboratory (SDL), was critical to proving the space flight readiness of the HOLMS instrument and provided the basis for a 2025 mission proposal to NASA's Payloads and Research Investigations on the Surface of the Moon: Stand Alone Landing Site Agnostic (PRISM SALSA) call.

The HOLMS prototype subsystem components during development: Left: The EMCCD detector mounted in JPL test dewar for preliminary characterization. Center: The spectrometer instrument during assembly and testing at SDL. Right: The detector readout electronics during benchtop testing at JPL.



DAS shines new light on seismology for Earth and the Moon

DAS uses fiber-optic cables to monitor seismic activity and has proven effective on Earth. On the Moon, a single cable could act as thousands of sensors, improving astronaut safety, mission planning, and reliability.



Noise performance comparison of current MDL testbed with commercial instrument.

Distributed acoustic sensing (DAS) techniques measure changes in the position of tiny imperfections in standard optical fiber cables by detecting the faint reflections that they produce. By doing so, the same glass strands that carry data can be simultaneously operated as a dense array of seismic sensors. DAS has transformed Earth seismology and geophysics by leveraging the ubiquitous telecommunications network and incorporating it into the seismic network. On the Moon, DAS offers a different, but equally compelling fit. The strong scattering of the lunar crust significantly distorts a seismic signal, even over very short distances, which makes it very difficult to track seismic wave propagation without a very dense array of sensors. DAS techniques excel at these measurements, converting a single optical fiber into thousands of sensors separated by only a few meters.

Operationally, a DAS system is also simpler than other seismometer array alternatives: All the sensing is done by a passive, robust element (the optical fiber), while the DAS instrument and electronics are confined to a single location such as a station, lander, or rover, where demands for power and thermal operation are more easily met. Consequently, developing a low-power, lunar-compatible DAS interrogator is a gateway technology that directly supports NASA's Artemis goals and broader lunar exploration strategy by enabling scalable, dense seismology with minimal hardware. It empowers the first steps towards a lunar seismic network. Its high-resolution data will be crucial for the science of the Moon's inner structure, including assessing tectonic activity, shallow structure, and impact risks. DAS can also be used to monitor the environment around Artemis landing sites, with implications for improved astronaut safety, the health monitoring of permanent structures and lunar habitats, and the development of moonquake early-warning systems, which can trigger automated safety protocols upon the detection of incoming moonquakes. DAS is also compatible with future infrastructure by integrating with power, communication, or telescope cables, making it a versatile asset for a long-term lunar presence. Conventional DAS interrogators are bulky instruments that weigh tens of kilograms, have >100 W power draws, and are not fit for operation over the broad thermal ranges of the Moon.

To adapt DAS technology for lunar applications, MDL is developing a miniaturized, flight-ready, phase-sensitive DAS system based on coherent optical time-domain reflectometry that matches the sensitivity of today's commercial instruments. By pairing the DAS interrogator with a specially designed, pre-engineered sensing fiber, the interrogator optical design, power, and processing requirements can be relaxed at the cost of reconfigurability. The fiber has a minimalistic and miniaturized design that simplifies processing and ruggedizes the instrument such that it can reach, and in specific scenarios overcome, the commercial devices' noise floors and performance at a fraction of the weight and power draw. This effort capitalizes on MDL's proven track record in chip-scale photonics and electronics and subsystem miniaturization, complemented by broader JPL expertise in space packaging and application-specific signal processing.

The proposed DAS system advances multiple high-priority NASA science goals identified in the 2023–2032 Planetary Decadal Survey and Artemis Science Objectives. It addresses Theme 1 (lunar origin and history) by imaging regolith and megaregolith structure, and it addresses Theme 2 (early geological processes) by resolving tectonic features and monitoring moonquakes. Objective 7m (real-time environmental monitoring) is directly addressed through DAS' ability to detect impacts and shallow quakes in real time. The project also complements the Farside Seismic Suite and aligns with Lunar Geophysical Network goals by laying the groundwork for networked seismology on the Moon.

DAS DATA MAY ONE DAY SUPPORT ENVIRONMENTAL MONITORING AROUND LUNAR LANDING SITES AND HABITATS

Custom and commercial CAMERAS for lunar exploration

A combination of custom and commercial off-the-shelf imaging technology can be used to create specialized imaging systems for future lunar missions. LunarCAM is an example of how these two technologies can be combined to quickly develop robust technology that can survive the harsh lunar environment.

With the current focus on lunar exploration, the demand for highly specialized imaging systems is becoming increasingly critical. These systems are essential for many practical applications, from autonomous navigation and terrain mapping to reconnaissance for both crewed and uncrewed science tasks. The lunar environment presents unique challenges that require innovative solutions, particularly when it comes to survival during the long, cold lunar night.

The lunar night lasts approximately 14 Earth days, and temperatures can fall as low as -200°C, especially at the poles. This extended period of darkness and extreme cold, combined with the high cost of power, poses a significant challenge for the durability and reliability of any equipment that operates on the surface. Therefore, the success of future lunar missions relies on a reliable imaging system capable of surviving the lunar night and performing essential tasks once daylight returns.

A critical part of the solution lies in advanced camera systems, and JPL's efforts are based on successful innovations already proven on Mars. The Enhanced Engineering Camera (EECAM), originally developed for the Perseverance rover for navigation, hazard avoidance, and cache sampling imaging, continues to operate flawlessly on the Martian surface. This success provides a strong foundation for adapting these high-reliability cameras for lunar missions.

A key milestone in adapting EECAM technology for lunar applications was the completion of a rigorous TVAC test funded by NASA's Game Changing Development (GCD) program. After a thorough parts review, the test subjected the Mars EECAM electronics to the extreme temperature swings expected on the Moon, ranging from +135°C to -200°C. After 80 cycles under these harsh conditions, mimicking a qualification program for a two-year deployment, the system survived without the use of power-intensive survival heaters. More impressively, post-test verification showed that the camera electronics were fully operational across a temperature range from +75°C to -55°C, making it a viable candidate for lunar operations over an extended period.

CUSTOM AND OFF-THE-SHELF CAMERA TECHNOLOGY WOULD SUPPORT FUTURE LUNAR MISSIONS

DEVICES FROM INSIDE AND OUTSIDE MDL ARE PACKAGED FOR FLIGHT AND ENGINEERED FOR INTEGRATION WITH A PAYLOAD

This test success underscores JPL's capability to deliver high-performance, reliable imaging systems that can withstand the harsh lunar environment. It serves as just one example of how JPL's camera integration experience can be leveraged to develop cutting-edge technology for lunar exploration.

Not all lunar missions require the highest levels of reliability. As such, JPL is also exploring other options, including commercial off-the-shelf (COTS) solutions. COTS cameras are not as robust as EECAM, but they do offer a cost-effective alternative for less-extreme environments or mission segments where lower reliability and higher risk are acceptable.

High-reliability cameras and flexible COTS systems can be used together to balance performance, cost, and risk for a variety of lunar mission requirements. For example, LunarCAM is a robust approach to lunar exploration with minimum development and fast turnaround time to readiness. With a proven track record of high-reliability cameras and a flexible strategy that includes high-reliability, flight-proven, and COTS-based options, MDL is prepared to meet the challenges of lunar missions, whether those challenges involve extreme cold, power limitations, or budget constraints. This dedication to tailoring the right imaging system for every mission is paving the way for future lunar exploration, ensuring success for astronauts and robotic missions alike. MDL's contribution to LunarCAM centers on packaging sensors for flight.

Off the shelf, into SPACE

As mission requirements and priorities have changed, the camera systems for the planned Mars Sample Return program have shifted from a more-custom solution to a commercial off-the-shelf platform that is now being rigorously tested. The lessons learned are informing camera design choices for future lunar missions.

Following the latest developments in the camera systems for the planned Mars Sample Return (MSR) program, several changes have been implemented to adapt to updated requirements, reduce complexity, and contain cost while maintaining imaging performance. Initially, the Mars 2020 HazCam EECAM architecture was to be repurposed for MSR, but new mission-specific constraints and opportunities have resulted in mechanical and electronic modifications that better suit the revised needs of the system.

The early MSR design needed to accommodate powered landing operations in a dust-rich environment. Consequently, a soft shroud was developed and integrated with a modified mechanical chassis. This modification allowed the camera body to physically couple to deployable covers designed to protect the optics and electronics during dust storms. Additionally, since several imaging tasks—like documenting sample tube status inside the orbiting sample (OS) container—occur in complete darkness inside the lander, a compact illuminator based on the Mars 2020 CacheCam illuminator was designed and added.

This active lighting ensures image clarity in the OS volume, including imaging the lid closure. However, as the mission design evolved, the camera system architecture also shifted. Imaging is now considered non-mission-critical, so the baseline hardware has transitioned to a COTS platform. These COTS cameras were used in the EDLCam system on Perseverance for its Entry, Descent, and Landing (EDL) footage, as well as in the SWOTCam system on the Surface Water and Ocean Topography (SWOT) mission to record solar panel and antenna deployments. They are still operational after over 1500 sols on the Martian surface.

On MSR, the COTS-based camera system is split between two major functions. The first is to capture the EDL sequence of the lander, from parachute deployment to surface touchdown. The second is surface operations, specifically monitoring the transfer of sealed sample tubes from Perseverance to the lander and imaging the tubes once secured in the OS system. The imaging of the OS container still requires imaging under dark conditions and will use the previously developed illuminator.

To mitigate the higher technical risk associated with using non-flight-qualified components in a Mars surface environment, TVAC testing is now underway for the COTS hardware. The cameras must demonstrate reliable functionality across the temperature cycles expected during both EDL and surface operations, even though they are not designated as mission critical.

In parallel, these developments are directly influencing camera system proposals for lunar applications. The lunar surface presents more extreme thermal challenges than does Mars.

MDL HAS PLAYED A KEY ROLE IN DEVELOPING THE ADVANCED IMAGING TECHNOLOGIES BEHIND JPL'S MOST HISTORIC SPACE CAMERAS, POWERING MISSIONS FROM HUBBLE REPAIR TO MARS EXPLORATION

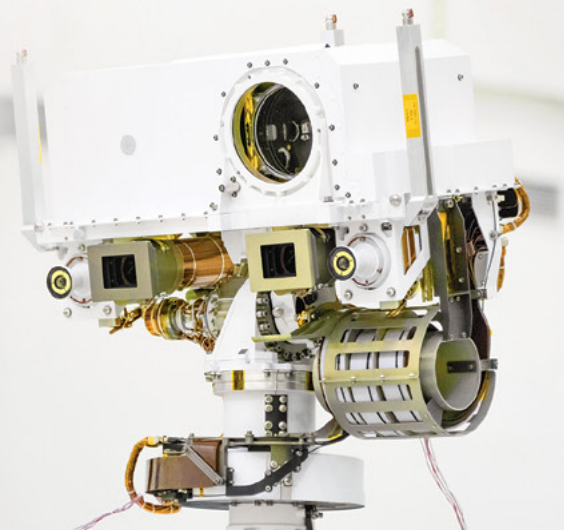
As part of the LunarCAM research effort, high-reliability EECAM electronics originally designed for Mars were subjected to extended thermal cycling tests. The test campaign simulated operations over two years on the Moon's surface, successfully validating these electronics across wider thermal swings.

This success supports the push to offer both high-reliability camera systems and cost-effective COTS-based alternatives for different mission categories. Robust EECAM platforms will be used for critical imaging tasks on long-duration lunar missions while COTS cameras, with their flexibility and fast development cycle, will be used for less-critical tasks.

In summary, MSR's camera system has transitioned to an architecture based on flight-proven COTS components, enhanced by mission-specific hardware such as a custom illuminator and mechanical interface modifications. These choices balance risk, cost, and capability. Lessons learned and hardware qualified through MSR are now informing proposals for camera deployments on upcoming lunar missions. This dual-use evolution between Mars and the Moon demonstrates the versatility of the imaging systems and the increasing maturity of integrating commercial hardware into planetary missions.

EECAMs for the Mars Sample Return Lander.

M2020 EECAM high-resolution camera mission images.



MDL

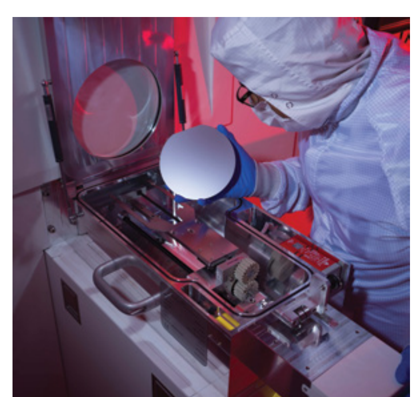
stays at the cutting edge by investing in state-of-the-art equipment

NEW EQUIPMENT WILL SUPPORT WAFER-SCALE PATTERNING AND MORE

MDL makes strategic investments in equipment that can offer a high long-term return. Investments made as a result of a 2021 assessment are beginning to yield benefits, ensuring MDL's continued position at the forefront of microdevice research, development, and fabrication.

MDL has maintained its unique leadership in microdevice manufacturing due to sustained investment in the facilities and equipment needed for research and development, prototyping, and delivery. These investments are required because semiconductor processing is a vibrant field that undergoes continuous evolutionary and revolutionary improvement. These improvements in turn offer the potential for substantial advances in the ability to make state-of-the-art microdevices, leading to enhanced capabilities. However, the budgets and floor space for these investments are constrained compared to the need. Therefore, MDL must plan carefully to ensure any money spent provides lasting upgrades.

In late 2021, a survey identified current and potential future weak points in MDL's processing equipment complement. Aging equipment in patterning (photoresist coating, optical lithography, and photoresist strip) and inductively coupled plasma (ICP) chlorine etching were highlighted as needing attention, in some cases urgently. At the same time, key facilities systems core to building and cleanroom operation (air handling, exhaust, compressed air, water, etc.) were also in need of renewal or replacement due to the wear and tear of 35 years of continuous operation. Between these two critical areas, the size and scope of the effort were significant. However, sustained investments, both large and small, over the past four years have yielded great progress in addressing these concerns.



Facilities and equipment projects can take time to complete; the configuration control required to ensure the safety of personnel and equipment in the face of fires, power outages, leaks, earthquakes, etc., necessitates a robust design and systems engineering process for every change. Additionally, semiconductor equipment has long lead times as part of the supply chain, leading to months-long delivery times. Thus, it can take 2–3 years for the benefits of an investment to be realized.

In 2025, many of the investments begun in fiscal years 2022 and 2023 came on line. The most recent of these new systems, an Oxford Cobra cryo etcher with an atomic layer etching (ALE) kit, provides state-of-the-art etching capabilities from -110°C to +400°C, including both optical emission and laser-based endpoint detection. The higher range in temperatures, the addition of hydrogen bromide (HBr) as a process gas, and the ALE capabilities have found immediate use in the processing of next-generation superconductor materials such as magnesium diboride (MgB_2), as well as optoelectronic devices based on lithium niobate or indium phosphide, which may power the interconnects of the next generation of quantum computing or sensing. A new SAMCO reactive ion etching (RIE) tool brought online at the beginning of 2025 has been successfully qualified for photoresist strip and other ashing-type cleaning applications. This tool forms the backbone of all superconducting-device- and e-beam-lithography-based fabrications at MDL.

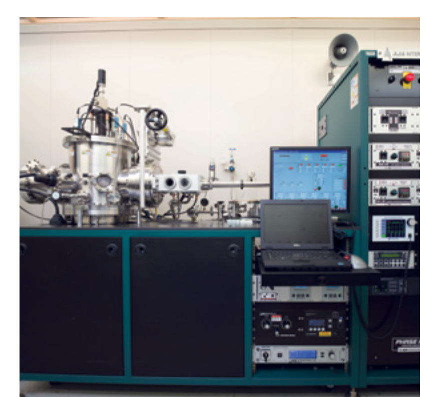
Additionally, a dedicated MgB_2 sputter system will enable a new class of high-temperature superconducting detectors at the wafer scale. The dedicated sputter deposition chamber will be capable of rapid turnarounds for process and film optimization in the search for high-performance, high-operating-temperature SNSPD-based wafer-scale device arrays. Breakthrough materials such as MgB_2 are often required to enable compelling new instrument capabilities. However, since forward or backward contamination is a concern with any new material, it is often necessary to have a dedicated piece of equipment to scope the material's promise and capability. Once these properties have been thoroughly studied, it may be possible to transition dedicated equipment into common use, a possible future for this system.

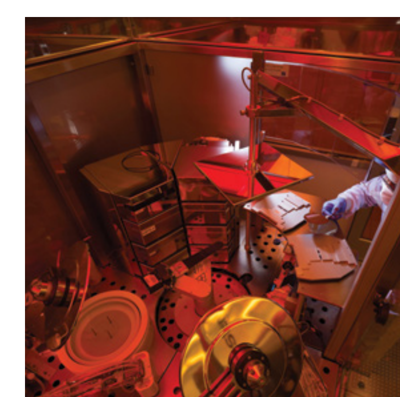
While investments in equipment and facilities are highly impactful, MDL has also focused on operational improvements enabled by NEMO lab management software. NEMO, in combination with MDL's Cypress monitoring system, has truly brought MDL into the digital age. Its real-time data have allowed MDL to very rapidly respond to prevent damage to in-process wafers and equipment if facilities interruption occur. Additionally, safety cameras have been placed in the cleanroom to provide visibility in case of an evacuation event. They were tested in a drill and reduced the time to locate "injured" employees from several hours to 15 minutes or less. With these facilities hardware upgrades and NEMO software, MDL is now far more resilient against all manner of internal and external disruptions.

SAFETY UPGRADES PROMOTE ROBUST RESPONSES TO DISRUPTIONS

The area of greatest need identified in 2021 was high-throughput optical lithography at the wafer scale. Fortunately, MDL secured investment to significantly upgrade and improve its wafer-scale patterning capability through the acquisition and soon-to-be-completed installation of an ASML PAS5500-1150C 90 nm node scanner. The scanner can also pattern down to 65 nm with off-axis illumination. These capabilities are currently only available at one other government facility: MIT's Lincoln Laboratory. JPL's capability to make wafer-scale devices is therefore singular. Some initial beneficiaries of this technological leap are the work on SNSPDs and meta-surfaces. These two technology areas combine small features that need to be integrated into detector surfaces, as well as the fabrication of large arrays of very fine wires and interconnects, which must be reliably repeated for a device to work. The ASML project work began in 2024, and the construction of a dedicated cleanroom for the new machine is about half complete as of 2025. It is likely that MDL will have a fully functional capability in 2026, allowing new microdevices to be realized.

MDL has purchased equipment that offers the potential of high future returns. Various equipment upgrades and facilities renewal projects are expected to have a lasting effect at MDL and enable hundreds of new devices and device architectures in the years to come.





Partnering for DISCOVERY

Creative innovations, excellence, and technology advances from MDL have been applied to the past, current, and future needs of NASA's collaborations.

Creative innovations and advanced technology developments at MDL provided enabling detectors and deliveries for NASA contributions to the European Space Agency (ESA)-led Herschel and Planck Space Observatory missions. Herschel and Planck were launched together on May 14, 2009. Significant scientific data were gathered during the missions, which ended in 2013 when the observatories' cryogenic coolant was depleted. Herschel provided knowledge about molecular species in space, and Planck significantly expanded our knowledge on the cosmic microwave background, a radiation field left over when light first coalesced after the big bang.

The Herschel Space Observatory had three instruments, two of which were enabled by MDL technology developments. First, HIFI was enabled by the long-term MDL development of superconductor-insulator-superconductor (SIS) mixers and MDL-fabricated gallium arsenide Schottky diodes for the primary submillimeter local oscillator sources.

THE MISSIONS SUPPORTED HAVE UNCOVERED INFORMATION ABOUT THE PAST, PRESENT, AND FUTURE OF OUR UNIVERSE

These mixers provided detectors at gigahertz and even terahertz frequencies that previously had not been attainable. Second, the Spectral and Photometric Imaging Receiver (SPIRE) depended on micro-mesh spider bolometers designed and fabricated at MDL.

MDL's contribution of micro-mesh spider bolometers for the High Frequency Instrument (HFI) on the Planck telescope was similar to that for Herschel's SPIRE; however, each of the 54 bolometers in the focal plane were assembled in individual packages, and 32 of the 54 bolometers were sensitive to a single polarization. The Planck telescope imaged the sky at six frequencies between 100 GHz and 857 GHz.

The knowledge and experience gained from the design, fabrication, and packaging of the superconducting detectors for Herschel and Planck were also applicable to the current ESA-led Euclid mission. Launched on July 1, 2023, with a nominal six-year mission duration, Euclid's objective is to better understand dark energy and dark matter by accurately measuring the accelerating expansion of the universe by measuring the redshift of galaxies over approximately a third of the sky.

MDL HAS PROVIDED ENABLING TECHNOLOGY FOR THE EUROPEAN SPACE AGENCY FOR OVER 15 YEARS

MDL manufactured flight silicon fan-out boards for the new cryogenic ASIC package. This silicon fan-out is necessary to interface the fine wire bond pitch on the ASIC with a wider wire bond pitch on the printed circuit boards. This ASIC hybrid assembly was qualified to survive thermal cycling to cryogenic temperatures.

Similarly, in October 2024, MDL delivered to the Contribution to ARIEL Spectroscopy of Exoplanets (CASE), the detector subsystem contribution to the Fine Guidance Sensors system instrument. This is part of the European Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) space telescope, which is planned to launch in 2029.

CASE will observe exoplanet transits in front of their host stars in the optical and near-infrared and accumulate the spectra of the exoplanets' atmospheres as the light of their host stars passes through the exoplanets' atmospheres. The CASE detector subsystem utilizes detectors and associated cryogenic electronics flight spares that NASA built for the ESA's Euclid mission.

CASE will enable ARIEL to observe clouds and hazes, which will help establish planetary climate, and provide a more comprehensive picture of the nearly 1000 exoplanet atmospheres ARIEL will observe.

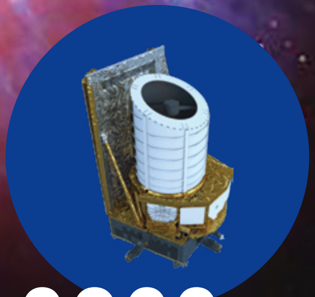
MDL Contribution

2009
Herschel
Space Observatory

SIS MIXERS, SCHOTTKY DIODES (HIFI), BOLOMETERS (SPIRE)

2009
Planck
Space Observatory

BOLOMETERS (HFI)



2023
Euclid
Space Telescope

SILICON FAN-OUT BOARDS, CRYO ASIC PACKAGING

2029
ARIEL
Exoplanet Observatory

CASE DETECTOR SUBSYSTEM USING EUCLID FLIGHT SPARES

MDL VISITING COMMITTEE

The Visiting Committee was initiated shortly after MDL's reorganization in 2007. Its membership comprises individuals with an enormous range of skills and experience. The committee's remit is not only to review past and current activities and plans but also to be proactive in giving advice.

The committee comes to MDL every two years and then produces a formal report. As with previous visits, their insights have proved very valuable and are much appreciated. MDL management listened to and is acting on their recommendations, which are taken very seriously.

Dr. Thomas L. Koch
Committee Chair
Dean, James C. Wyant College of Optical Sciences
University of Arizona

Dr. Paula Grunthaner
Committee Co-Chair
Retired, Manager of Mission System Concepts Section and former Manager, MDL Microdevices Section
Jet Propulsion Laboratory

Dr. Ned Bair
Research Appointment at UCSB
Chief Scientist & Portfolio Manager, Earth Intelligence Group
Technical Fellow, Leidos
UC Santa Barbara

Prof. Ben Mazin
Susan and Bruce Worster Chair in Experimental Physics
University of California

Dr. Susan M. Lunte
Ralph N. Adams Distinguished Professor of Chemistry, Director of the Adams Institute for Bioanalytical Chemistry, Director, NIH COBRE Center for Molecular Analysis of Disease Pathways
University of Kansas

Dr. James Beletic
Chief Scientific Officer, Digital Imaging Space
Teledyne Space Imaging

Prof. Karl Berggren
Faculty Head of Electrical Engineering
Massachusetts Institute of Technology

Dr. Lindy Elkins-Tanton
Director, Space Sciences Laboratory, School of Earth & Space Exploration
UC Berkeley

Dr. Rick McCormick
Senior Manager, Advanced Semiconductor Technologies
Sandia National Laboratories

Prof. Azita Emami
Andrew and Peggy Cherng Professor of Electrical Engineering and Medical Engineering
California Institute of Technology

Dr. Eric R. Fossum
John H. Krehbiel Sr. Professor for Emerging Technologies
Vice Provost, Office of Entrepreneurship and Technology Transfer Director, PhD Innovation Program
Dartmouth College

Dr. Harris J. Hall
Technical Lead, Sensors Directorate, Electro-Optic and Infrared Technologies Branch
Air Force Research Lab

Dr. David Paige
Professor of Planetary Science
UC Los Angeles

APPENDIX

Peer-Reviewed Journal Publications

1. Alonso-delPino, M., Bosma, S., Jung-Kubiak, C., Bueno, J., Chattopadhyay, G., & Llombart, N. (2024). A transmit lens array with high-gain and beam-steering capabilities at submillimeter wavelengths. IEEE Transactions on Terahertz Science and Technology, 14(1).

2. Bosma, S., van Berkel, S. L., Alonso-delPino, M., Blanco, D., Jung-Kubiak, C., Lin, R., Chattopadhyay, G., Siles, J. V., & Llombart, N. (2024). Dual-band submillimeter-wave leaky-wave lens antenna for heterodyne cometary mapping. IEEE Transactions on Terahertz Science and Technology, 15(2).

3. Day, P. K., Cothard, N. F., Albert, C., Foote, L., Kane, E., Eom, B. H., Basu Thakur, R., Janssen, R. M. J., Beyer, A., et al. (2024). A 25-micrometer single-photon-sensitive kinetic inductance detector. Physical Review X, 14(4), Article 041005. https://doi.org/10.1103/PhysRevX.14.041005

4. Drevinskas, T., Berg, A., Noell, A. C., Ferreira Santos, M. S., Mora, M. F., & Willis, P. A. (2024). Analytical Chemistry, 96(52), 20343–20347. https://doi.org/10.1021/acs.analchem.4c04643

5. Faramarzi, F., Stephenson, R., Sypkens, S., Eom, B. H., LeDuc, H., & Day, P. (2024). A 4–8 GHz kinetic inductance traveling-wave parametric amplifier using four-wave mixing with near quantum-limited noise performance. APL Quantum, 1(3), 036107. https://doi.org/10.1063/5.0208110

6. Herath, K., Nirmalathas, A., Gunapala, S. D., & Premaratne, M. (2024). A dual-signaling architecture for enhancing noise resilience in Floquet engineering-based chip-scale wireless communication. IEEE Journal on Selected Areas in Communications, 42(8), 2039–2053. https://doi.org/10.1109/JSAC.2024.3399206

7. Herath, K., Gunapala, S. D., & Premaratne, M. (2024). Investigating the impact of polarization on surface plasmon polariton characteristics in plasmonic waveguides under periodic driving fields. Physica Scripta, 99(4), Article 045014. https://doi.org/10.1088/1402-4896/ad3022

8. Jornet, J. M., Petrov, V., Wang, H., Popovic, Z., Shakya, D., Siles, J. V., & Rappaport, T. S. (2024). The evolution of applications, hardware design, and channel modeling for terahertz (THz) band communications and sensing: Ready for 6G? arXiv preprint arXiv:2406.06105.

9. Khanal, S., Rahiminejad, S., Lee, C., Kooi, J. W., Lin, R., & Chattopadhyay, G. (2024). A waveguide-based variable attenuator for terahertz applications. IEEE Transactions on Terahertz Science and Technology, 14(2).

10. Maestrini, A., Siles, J. V., Lee, C., Lin, R., & Mehdi, I. (2024). A 2 THz room temperature bias-able Schottky mixer. IEEE Transactions on Terahertz Science and Technology.

11. Millán, L. F., Lebsock, M. D., Cooper, K. B., Siles, J. V., Dengler, R., Rodriguez Monje, R., Nehrir, A., et al. (2024). Water vapor measurements inside clouds and storms using a differential absorption radar. Atmospheric Measurement Techniques, 17(2), 539–559.

12. Rahiminejad, S., van Berkel, S., Lin, R., Khanal, S., Jung-Kubiak, C., Chattopadhyay, G., & Rais-Zadeh, M. (2024). 500–750 GHz contactless rotating MEMS single-pole double-throw waveguide switch. Journal of Microelectromechanical Systems, 33(5), 532–542.

13. Shanks, D. N., Allmaras, J. P., Patel, S. R., Korzh, B. A., Wollman, E. E., Greer, F., Beyer, A. D., & Shaw, M. D. (2024). Line width narrowing of superconducting nanowire single-photon detectors using atomic layer etching. Applied Physics Letters, 126(11), 112602. https://doi.org/10.1063/5.0252913

14. Siles, J. V., Maestrini, A. E., Lee, C., Lin, R., & Mehdi, I. (2024). First demonstration of an all-solid-state room temperature 2-THz front end viable for space applications. IEEE Transactions on Terahertz Science and Technology, 14(5), 607–612.

15. Socuellamos, J. M., Rodriguez Monje, R., Cooper, K. B., Lebsock, M. D., Nagaraja, S. P. M., Siles, J. V., Beauchamp, R. M., & Tanelli, S. (2024). A G-band Doppler radar for atmospheric profiling. IEEE Transactions on Geoscience and Remote Sensing, 62.

16. Soibel, A., Ting, D. Z., Khoshakhlagh, A., Bouschet, M., Fisher, A. M., Pepper, B. J., & Gunapala, S. D. (2024). Hole diffusion length and mobility of a long wavelength infrared InAs/InAsSb type-II superlattice nBn design. Applied Physics Letters, 125(17), 171111. https://doi.org/10.1063/5.0236096

17. Ting, D. Z., Soibel, A., Khoshakhlagh, A., Keo, S. A., Fisher, A. M., Pepper, B. J., Rafol, S. B., Hill, C. J., & Gunapala, S. D. (2024). The effect of p-doping in mid- and long-wavelength InAs/InAsSb superlattice complementary barrier infrared detectors. Applied Physics Letters, 125(19), 191106. https://doi.org/10.1063/5.0236130

18. Van Berkel, S., Khanal, S., Rahiminejad, S., Jung-Kubiak, C., Maestrini, A. E., & Chattopadhyay, G. (2024). MEMS phase shifters for THz beam-scanning: Demonstration with a 500–600 GHz phased array with leaky-wave feeds. IEEE Transactions on Terahertz Science and Technology, 14(6), 830–842.

19. Vincent, L. N., Fayolle, E. C., Hodyss, R., et al. (2024). Bacterial spore morphology remains highly recognizable after exposure to simulated Enceladus and Europa surface conditions. Communications Earth & Environment, 5(688). https://doi.org/10.1038/s43247-024-01872-z

Published Conference Publications

1. Ardila, D., Shkolnik, E., Scowen, P., Ramiaramanantsoa, T., Barman, T., Bowman, J., Basset, C., Gamaunt, J., Gregory, D., Jacobs, D., Jensen, L., Jewell, A., Kolopanis, M., Knapp, M., Kyne, G., Ladwig, C., Llama, J., Meadows, V., Nikzad, S., Peacock, S., Struebel, N., & Swain, M. (2024). Photometric calibration in the ultraviolet of the Star-Planet Activity Research CubeSat (SPARCS). In Proceedings of SPIE 13093, Space Telescopes and Instrumentation 2024: Ultraviolet to Gamma Ray (Paper 1309338). https://doi.org/10.1117/12.3019065

2. Ballew, C., van Berkel, S., Khanal, S., & Chattopadhyay, G. (2024, March). Inverse-designed volumetric silicon meta-optics. In International Symposium on Space THz Technology (ISSTT 2024), Charlottesville, VA, United States.

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14. Maestrini, A., et al. (2024, April 7–11). 2 THz receivers for thermospheric winds. Presented at the International Symposium on Space THz Technology (ISSTT 2024), Charlottesville, VA, United States.

15. O'Sullivan, D., Fleming, B., Indahl, B., Vorobiev, D., Bowen, M., France, K., Escobar, S., Wong, Y. H. V., Carlson, E., Gopinathan, S. A., & Tumlinson, J. (2024). Observing modes of the SPRITE 12U CubeSat: A probe of star formation feedback with far-UV imaging spectroscopy. In Proceedings of SPIE 13093, Space Telescopes and Instrumentation 2024: Ultraviolet to Gamma Ray (Paper 1309332). https://doi.org/10.1117/12.3020332

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17. Towfic, Z., Ogbe, D., Janamian, S., Jongeling, A., Sheldon, D., & Sauvageau, J. (2024, April 30–May 2). The JPL Snapdragon co-processor. In Interplanetary Small Satellite Conference (ISSC 2024).

18. Tuttle, S. E., Corlies, L., Faerman, Y., Fleming, B., Hennessy, J., Mandeville, T., Mesbahi, M., McPhate, J., McQuinn, M., Nikzad, S., & Quijada, M. (2024). The initial design of Maratus: A 12U narrowband imager for mapping the circumgalactic medium. In Proceedings of SPIE 13093, Space Telescopes and Instrumentation 2024: Ultraviolet to Gamma Ray (Paper 130930G). https://doi.org/10.1117/12.3020547

19. van Berkel, S., Jung-Kubiak, C., Kooi, J., Peralta, A., Mehdi, I., & Chattopadhyay, G. (2024, December). Planar and modular silicon package suitable for future large-format 1.9 THz heterodyne arrays. In 2024 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON) (pp. 1–3), Hyderabad, India. https://doi.org/10.1109/MAPCON.2024

20. Ting, D. Z.-Y. (2024, August 12–16). InAs/InAsSb type-II strained-layer superlattice complementary barrier infrared detector (CBIRD). Invited talk presented at the Quantum Structure Infrared Photodetector (QSIP 2024) International Conference, Santa Barbara, CA.

Invited Presentations and Seminars

1. Gunapala, S. D. (2024, December 6). Advances in infrared detection technologies for remote sensing applications. Seminar presented at Monash University, Melbourne, Australia.

2. Gunapala, S. D. (2024, December 8–11). Applications of T2SL barrier infrared detectors in Earth remote sensing instruments. Paper presented at the International Symposium on Semiconductor Optoelectronics and Nanotechnology, Canberra, Australia.

3. Gunapala, S. D. (2025, April 14). Antimonides type-II focal plane arrays for Earth remote sensing instruments. Invited paper presented at SPIE Defense and Commercial Sensing, Orlando, FL.

Contributed Presentations

1. Gunapala, S. D., Johnson, W., Ting, D. Z., Soibel, A., Rafol, S., Keo, S., Pepper, B., Hill, C., Kalashnikova, O., Garay, M., Davies, A., David, C., Babu, S., & Ghuman, P. (2024, July). Compact-Fire Infrared Radiance Spectral Tracker (c-FIRST) for SmallSat platform. Paper presented at IGARSS 2024 – IEEE International Geoscience and Remote Sensing Symposium, Athens, Greece.

2. Gunapala, S. D., Johnson, W., Ting, D. Z., Soibel, A., Rafol, S., Keo, S., Pepper, B., Hill, C., Kalashnikova, O., Garay, M., Davies, A., David, C., Babu, S., & Ghuman, P. (2024, May 27–31). Compact-Fire Infrared Radiance Spectral Tracker (c-FIRST). Paper presented at ESA Small Satellites Systems and Services Symposium (4S 2024), Palma de Mallorca, Spain.

3. Gunapala, S. D., Johnson, W., Ting, D. Z., Soibel, A., Rafol, S., Keo, S., Pepper, B., Hill, C., Kalashnikova, O., Garay, M., Davies, A., David, C., Babu, S., & Ghuman, P. (2024, September 17). Compact-Fire Infrared Radiance Spectral Tracker (c-FIRST). Paper presented at SPIE Sensors + Imaging, Edinburgh, United Kingdom.

4. Gunapala, S. D., Ting, D. Z., Soibel, A., Rafol, S., Keo, S., Pepper, B., Hill, C., Kalashnikova, O., Garay, M., Davies, A., David, C., Babu, S., & Ghuman, P. (2024, August 18–22). Applications of T2SL barrier infrared detectors for SmallSat platforms. Paper presented at SPIE Optics + Photonics, San Diego, CA.

5. Gunapala, S. D., Wright, R., Lucey, P., Nunes, M., Rafol, S., Ting, D. Z., Flynn, L., Ferrari-Wong, C., Soibel, A., & George, T. (2024, May 27–31). The HYTI mission. Paper presented at ESA Small Satellites Systems and Services Symposium (4S 2024), Palma de Mallorca, Spain.

6. Gunapala, S. D. (2025, June 10–11). Airborne test of c-FIRST over Los Angeles fires. Paper presented at the NASA Earth Science Technology Forum, Virtual meeting.

Awards and Recognition by External Organizations

1. High Operating Temperature–Barrier Infrared Detectors (HOT-BIRD or HOT-SLS) technology developed at JPL was inducted into the United States Space Foundation Hall of Fame at the 40th Space Symposium, held in Colorado Springs on June 9, 2025. JPL Director David Gallagher and Richard Cook attended the event. Gallagher remarked, "You made JPL very proud in front of the U.S. and European space communities." [Source: https://www.spacefoundation.org/2025/02/25/2025-space-technology-hall-of-fame/

2. Harrysson Rodrigues, I., Gabritchidze, B., Yi, L., Kangaslahti, P. P., Babenko, A. A., Kooi, J. W., & Minnich, A. (2024). Next generation ultra-low noise HEMTs for radio communications and science. Awarded Topical R&TD funding.

3. Jung-Kubiak, C. (2024). Elected as a board member for IEEE Access, an open-access multidisciplinary journal. She will serve a three-year term through December 2027.

New Technology Reports

1. Bush, N., & Nikzad, S. (2024). Massively parallel skipper devices (NTR No. 53179).

2. Hoenk, M. E., Jewell, A. D., & Rahiminejad, S. (2024, November 12). Molecular beam epitaxial growth of silicon on textured surfaces (NTR No. 53339).

3. Karasik, B.. (2024). An HEB terahertz mixer with the negative electro-thermal feedback (NTR No. 53000).

Book Contributions

1. Jung-Kubiak, C., Rahiminejad, S., & Chattopadhyay, G. (2024). MEMS-based terahertz components and systems: Bridging the terahertz gap with microelectromechanical systems. In Comprehensive Microsystems (2nd ed., 3-volume set). Elsevier.

2. Kraus, H., & Gottscholl, A. (2024). Nanophotonics with diamond and silicon carbide for quantum technologies (Chapter 20, p. 389). In Nanophotonics Series. Elsevier. (ISBN: 9780443137174)

Patents

1. Bush, N., & Nikzad, S. (2024, August 13). Massively parallel skipper devices (Provisional patent application filed; CIT File No. CIT-9200-P).

2. Jones, T. J., & Nikzad, S. (2024, September 10). Imaging in curved arrays: Methods to produce free-formed curved detectors (U.S. Patent No. 12,087,803 B2).

MDL Equipment Complement

Material Deposition

- KJL Indium Evaporator
- Denton Indium Evaporator
- Sloan E-beam Evaporator
- AJA UHV E-beam Evaporator
- TSC E-beam Evaporator
- Veeco E-beam Evaporator
- Xiron E-beam Evaporator
- Temescal E-beam Dielectric Evaporator
- Angstrom E-beam/Radak Evaporator
- Temescal E-beam IR detector
- Lesker #1 UHV Sputtering System (SIS)
- Lesker #2 UHV Sputtering System (SIS)
- Lesker Silicon Dioxide Sputter (Low Loss Dielectric) UHV Sputtering System (SIS)
- AJA Dielectric Sputtering System
- AJA Metal Sputtering System
- AJA Co-evaporator Bolometer
- Hummer Sputter System
- CHA Aluminum Evaporator
- Oxford High Density ICP CVD Dielectric
- Tystar LPCVD (Oxide/Nitride/Oxynitride)
- Plasma-Therm 790 PECVD
- Beneq TFS200 Atomic Layer Deposition System with Meaglow Hollow Cathode Plasma Upgrade
- Oxford OpAL Atomic Layer Deposition System
- Thermal Evaporation Enhanced-ALD
- Epi GEN III Sb MBE
- VEECO GenXcel III-V MBE
- VEECO Gen 200 8" Si MBE
- Wet/Dry Silicon Oxidation Manual Furnaces
- Solaris RTP Rapid Thermal Processor
- CNT Growth CVD 1
- CNT Growth CVD 2

Lithography

- ASML Scanner PAS5500 – 1150C (0.09um or 90nm)
- Canon EX3 Stepper (w/EX4 optics) (0.25um)
- Canon i4 Stepper (w/EX4 optics) (0.75um)
- Canon EX6 Stepper with 4" to 6" wafer size conversion kit (0.18 um)
- Heidelberg MLA 150 (200mm + Die by Die)
- Heidelberg MLA 150 (150 square mm max)
- MJB3 Backside IR
- MA-6 #1 (UV300)
- MA-6/BA-6 #2 (UV400)
- Solar Semi Coat/Bake with EBR
- Gamma Coat/Bake and Developer
- Osiris Spinner Basixx
- Solitec Resist Spinner
- Headway Spinner
- Tractix Wafer Track
- Sonotek Photoresist Spray Coater
- Thermal bake (Blue Oven)
- YES HMDS Vapor Prime Oven
- Yield Engineering Systems Eco –Clean Plasma Strip
- Ozone Cleaner
- Novascan Ozone Cleaner (2)
- S-Cubed Lift Off High Pressure Spray
- Branson Plasma Asher
- Tepla Microwave Asher

Characterization

- Zeiss Axiophot Microscope
- Zeiss Axiotron Microscope
- Nikon Eclipse L200 Microscope
- Mcbain/AST IR Microscope
- Woollam Spectroscopic Ellipsometer
- Keyence Microscope
- Nanospec Optical Profilometer
- Filmetrics F20-UV Film Measurement System
- Zygo ZeMapper
- Bruker/Wyco Interferometer
- FSM Film Stress Measurement
- Surfscan 6220 Wafer Particle Mapper
- Filmetrics F20-UV Film Measurement System
- Filmetrics F54: Automated Thin-Film Thickness Mapper
- Digital Instruments Atomic Force Microscope
- Park NX20 Atomic Force Microscope (AFM)
- Rame-hart Contact Angle Measurement
- Alphastep 500 Profilometer
- Dektak D-XTA Profilometer
- Hitachi Regulus 8230 SEM
- Surface Science XPS
- Xpert X-ray Diffraction System
- Leighton Non-Contact 4-Point Probe
- Automated Probe Stations
- Bluefors Cryogen-Free Dilution refrigerator
- CPX Cryo-Probe Station Lakeshore
- Ontos 7 Oxide Removal
- SurfX Surface Activation
- Diamond Point Turning
- Strausbaugh Chemical Mechanical Polisher
- CO2 Critical Point Dryer
- Polishing Station for GaAs/Silicon
- Allied Tech Polishing Stations for GaAs FPA Thinning
- Spin Rinser Dryer; RHETECH, Semitool
- Spin Rinser Dryer; RHETECH, Semitool

Etching

- SPTS Rapier DRIE
- Plasma-Therm Versaline DSE
- STS (DRIE) Deep Trench Reactive Ion Etcher
- Apex ICP Etcher Plasma-Therm Fl2-ICP
- Plasma Tech Fluorine RIE/Asher
- Unaxis Chlorine ICP Etcher
- Unaxis Fluorine ICP Etcher
- Xenon Difluoride Etcher
- Oxford Cl2 ICP/ALE Etcher
- Samco O2 RIE
- Oxford Black Silicon ICP/ALE

Others

- Commonwealth Ion Mill
- EVG 520IS Anodic Wafer bonder
- AB Wafer Bonder (Electronic Visions)
- SET FC300 (Flip Chip Bonder)
- Wafer Demounting De-Fixxo M20
- Finetech Large Area Bump Bonder with Ultrasonic Upgrade
- DISCO 320 Wafer Dicer #1
- DISCO 321 Wafer Dicer #2
- Blue Tape Machine with Pic and Place
- EVG 520IS Wafer Bonder (Refurbished)
- Westbond Wire Bonder

MDL

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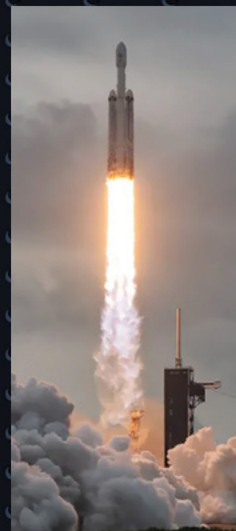
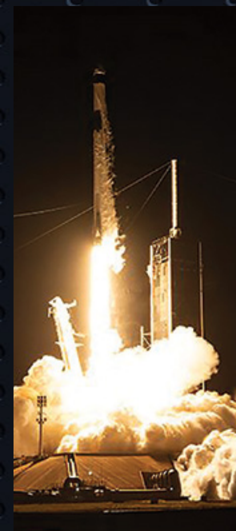
SPACECRAFT FIRE SAFETY EXPERIMENT-VI
COMBUSTION PRODUCT MONITOR
NG-19 CYGNUS
08.01.23 LAUNCH
Testing from 12.22.23 to 12.24.23



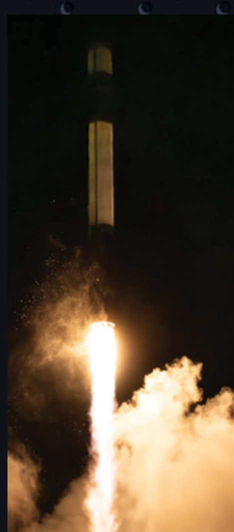
PSYCHE
DEEP SPACE OPTICAL COMMUNICATION
SpaceX FALCON HEAVY
10.13.23



ISS SAM
INTERNATIONAL SPACE STATION SPACECRAFT ATMOSPHERIC MONITOR TECHNOLOGY DEMONSTRATION UNIT 2 (TDU2)
SpaceX CRX-29
11.09.23

FORGE
FLUIDIC OPERATIONS IN REDUCED GRAVITY EXPERIMENT
BLUE ORIGIN NS-24
12.19.23

HYTI CUBESAT
HYPERSPECTRAL THERMAL IMAGER MDL HOT-BIRD LWIR FPA AND DEWAR COOLER ASSEMBLY
SpaceX CRS-30 03.21.24
Deployed from ISS 04.18.24



PREFIRE
POLAR RADIANT ENERGY IN THE FAR-INFRARED EXPERIMENT
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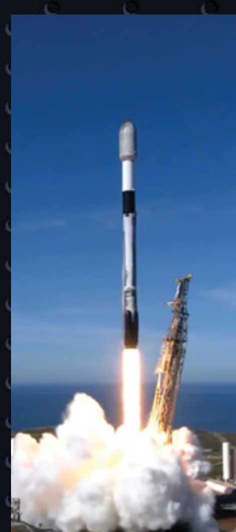
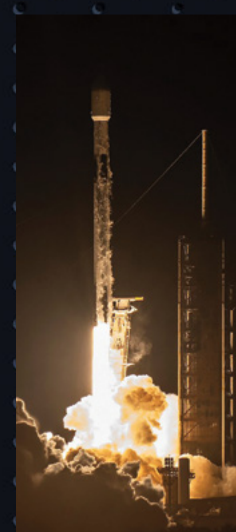
05.25.24
ELECTRON KS PREFIRE 2
06.05.24



TANAGER-1
IMAGING SPECTROMETER
SpaceX FALCON 9
08.16.24

EUROPA CLIPPER MISE
MAPPING IMAGING SPECTROMETER FOR EUROPA
SpaceX FALCON HEAVY
10.14.24



LUNAR TRAILBLAZER HVM^3:
HIGH-RESOLUTION VOLATILES AND MINERALS MOON MAPPER
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